



Ivan Renev

**AUTOMATION OF THE CONCEPTUAL DESIGN
PROCESS IN CONSTRUCTION INDUSTRY USING
IDEAS GENERATION TECHNIQUES**



Ivan Renev

AUTOMATION OF THE CONCEPTUAL DESIGN PROCESS IN CONSTRUCTION INDUSTRY USING IDEAS GENERATION TECHNIQUES

Dissertation for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium 1314 at Lappeenranta-Lahti University of Technology LUT, Lappeenranta, Finland on the 10th of May, 2019, at noon.

Acta Universitatis
Lappeenrantaensis 850

Supervisor Professor Leonid Chechurin
LUT School of Engineering Science
Lappeenranta-Lahti University of Technology LUT
Finland

Reviewers Professor Iouri Belski
School of Engineering
Royal Melbourne Institute of Technology
Australia

Professor Pavel Livotov
Department of Mechanical and Process Engineering
Offenburg University of Applied Sciences
Germany

Opponent Professor Denis Cavallucci
Department of Mechanics
INSA Strasbourg - National Institute of Applied Sciences
France

ISBN 978-952-335-364-0
ISBN 978-952-335-365-7 (PDF)
ISSN-L 1456-4491
ISSN 1456-4491

Lappeenranta-Lahti University of Technology LUT
LUT University Press 2019

Abstract

Ivan Renev

Automation of the conceptual design process in construction industry using ideas generation techniques

Lappeenranta 2019

92 pages

Acta Universitatis Lappeenrantaensis 850

Diss. Lappeenranta-Lahti University of Technology LUT

ISBN 978-952-335-364-0, ISBN 978-952-335-365-7 (PDF),

ISSN-L 1456-4491, ISSN 1456-4491

Early design stage in Construction projects is a crucial part of the sophisticated long-term design process. Here many fundamental and critical decisions are being taken. The more successful and innovative solutions are developed during this stage, the more advanced, effective, and less costly design is gained. Those solutions can be found by using different tools for ideas generation and the Theory of Inventive Problem Solving (TRIZ) is believed to be one of the most effective and well-structured problem-solving techniques. In the digital century it is reasonable to link modern construction design software with ideas generation techniques in order to enhance and automate design creativity. Nowadays Building Information Modelling (BIM) became a popular stream in the construction design. Existing BIM software have range of instruments enabling designers to bring all their knowledge and experience into projects but, however, such software does not support users in searching for nontrivial conceptual ideas for design. That is why the ideas generation stage is still a separate, not automated and human-dependent part of the construction design.

Thus, there is no professional software which would automate the decision-making process at early design phases including search for not only optimal and reliable solutions but also for inventive ones. On the other hand, BIM and graphical programming for design are state-of-the art in the modern construction design and Computer-Aided-Invention (CAI) software is becoming more popular in different disciplines. Merging this with existing inventive techniques could add artificial intelligence into the design software and enhance and automate design creativity in the conceptual design stage.

In the dissertation a method for automation of the conceptual design process of framed bearing structural systems has been developed, implemented and tested. The method consists of three key steps: shape creation, function analysis and contradiction analysis. First, the theoretical grounds for the development of the proposed methodology are justified in the thesis. After that, suggestions are made on the ideology of the method and it is technically implemented using modern design software. Finally, the method is tested on a case study and evaluated using a survey. The results show that the proposed approach reduces design time and increases effectiveness of the process. Further it is proposed to generalise method and increase its functionality.

Keywords: conceptual design, construction, BIM, TRIZ, automation

Acknowledgements

This work was carried out in the School of Engineering Science at Lappeenranta-Lahti University of Technology LUT, Finland, between April 2015 and April 2019. Working on the thesis is a great opportunity for personal development, learning new things and meeting interesting people whom I would like to acknowledge.

First of all, I would like to express my sincere gratitude to my supervisor Leonid Chechurin for his endless support and mentoring.

I would like to thank doctoral students Nikolai Efimov-Soini and Iuliia Shnai from Lappeenranta-Lahti University of Technology LUT for their organizational assistance and increasing my motivation. I am also grateful to Elena Perlova, former master student from Saint-Petersburg State Polytechnic University, for her contribution in technical realization of the developed approach for conceptual design stage automation.

I am thankful for the financial support that I have received from the Research Foundation of Lappeenranta-Lahti University of Technology LUT that made it possible to attend the international conferences and present this research to a wide audience. Thus, thanks to all colleagues whom I met on the conferences for your fruitful feedback that helped me to improve the research. I would also like to acknowledge the Finnish National Agency for Education for the positive decision on the financial support of this project and the Finnish Funding Agency for Innovation and its program FiDiPro for the financial support.

My warmest thanks to Professor Pavel Livotov and Professor Iouri Belski for acting as the preliminary examiners of this dissertation and for constructive feedback.

I would like to thank all my former and current teachers and colleagues. One way or another you all contributed to my development that has materialized in this dissertation.

I am deeply thankful to my parents, family and friends. Special thanks to my wife for her understanding and support and my son who was born in the same month when I applied for the doctoral studies, for giving me inspiration to go further.

Ivan Renev

April 2019
Lappeenranta, Finland

Dedicated to my mother Valentina

...you are always on my mind...

Contents

Abstract

Acknowledgements

Contents

List of publications	9
List of figures	11
List of tables	13
List of abbreviations	15
1 Introduction	17
1.1 Research background	17
1.1.1 Early design stage in construction	17
1.1.2 Building Information Modelling	18
1.1.3 Theory of Inventive Problem Solving.....	18
1.2 Research objectives and research questions	20
1.3 Focus of the thesis	21
1.4 Structure of the thesis	22
2 State of the art	25
2.1 Demand of innovation in construction	25
2.2 Application of TRIZ in construction	26
2.2.1 Development of construction technologies.....	27
2.2.2 Design of new structures and construction materials.....	28
2.2.3 Construction project management and value engineering	30
2.3 Automation of conceptual design in construction	32
2.4 Literature review summary	35
3 Model development	37
3.1 Shape creation	39
3.2 Function Analysis of a BIM	41
3.2.1 Interaction matrix	41
3.2.2 Determination functions of elements	43
3.2.3 Function diagram	48
3.3 Ranking	53
3.3.1 The first ranking rule.....	53
3.3.2 The second ranking rule	54
3.3.3 The third ranking rule	55
3.4 Trimming.....	56
3.5 Contradiction analysis	58

3.6	Chapter conclusion	62
4	Results	65
4.1	Evaluation of the proposed approach	65
4.1.1	Survey design	65
4.1.2	Survey results	66
4.1.3	Survey results analysis.....	70
4.2	Case study	70
4.2.1	Experimental model descriptions	70
4.2.2	Interaction and function matrices construction	71
4.2.3	Function diagram creations	73
4.2.4	Ranking	73
4.2.5	Trimming	75
4.2.6	Contradiction analysis	76
4.2.7	Case study conclusion	76
5	Summary of the publications	77
5.1	Interconnections between the publications	77
5.2	Publication I: Application of TRIZ in Building Industry: Study of Current Situation	79
5.2.1	Study objective	79
5.2.2	Main contribution	79
5.3	Publication II: Computer-aided conceptual design of building systems. Linking design software and ideas generation techniques	80
5.3.1	Study objective	80
5.3.2	Main contribution	80
5.4	Publication III: Early design stage automation in Architecture-Engineering-Construction (AEC) projects	81
5.4.1	Study objective	81
5.4.2	Main contribution	81
5.5	Publication IV: Evaluation of a novel approach for automated inventive conceptual design of building structures	82
5.5.1	Study objective	82
5.5.2	Main contribution	82
6	Discussion and conclusion	83
6.1	Answering the research questions	83
6.2	Contribution of the research	85
6.3	Limitations of the research	85
6.4	Future research directions.....	86
	References	87
	Appendices	
	Publications	

List of publications

This thesis is based on the following papers. The rights have been granted by publishers to include the papers in dissertation.

- I. Renev, I., and Chechurin, L., (2016). Application of TRIZ in Building Industry: Study of Current Situation. *Procedia CIRP*, 39, pp.209–215.

The paper was accepted following a double-blinded review of the full text. The article was presented at the 15th international conference of the European TRIZ association ETRIA, Berlin (October 26-29, 2015).

- II. Renev, I., (2019). Computer-aided conceptual design of building systems. Linking design software and ideas generation techniques. In *Advances in Systematic Creativity. Creating and Managing Innovations (1st ed., Chapter 13, pp. 201-224)*. Chechurin, L., Collan, M. (Eds.), London: Palgrave Macmillan.

The publication acceptance was based on a double blinded review of the full text. Materials were presented at the 16th international conference of the European TRIZ association ETRIA, Wrocław (October 24-27, 2016) and the 17th international conference of the European TRIZ association ETRIA, Lappeenranta (October 4-6, 2017).

- III. Renev, I., Chechurin, L., Perlova, E., (2017). Early design stage automation in Architecture-Engineering-Construction (AEC) projects. *Proceedings of the 35th eCAADe Conference, Volume 1*, pp. 373–382.

The publication was accepted following a double-blinded review of the extended abstract. The article was presented at the 35th annual international conference of eCAADe – Educational and research in Computer Aided Architectural Design in Europe, Rome (September 20-22, 2017).

- IV. Renev, I., (2018). Evaluation of a novel approach for automated inventive conceptual design of building structures. *Journal of Civil Engineering and Architecture*, 12 (2018), pp. 550–562.

The article was accepted following a double-blinded review of the full text.

Ivan Renev is the principal author and investigator of all papers included in this dissertation. He is also the corresponding author for all included publications.

List of figures

Figure 1.1: *Distribution of TRIZ tools usage in industrial sectors (Cavallucci 2009);*

Figure 1.2: *Euler diagram showing the research focus;*

Figure 2.1: *Importance of innovations for the future of construction (Dale 2007);*

Figure 3.1: *Roadmap of the conceptual design process;*

Figure 3.2: *(a) Result of a graphical program (tall building structure). (b) Interface of the graphical program;*

Figure 3.3: *Set #1 of initial parameters and corresponding results of a graphical program;*

Figure 3.4: *Set #2 of initial parameters and corresponding results of a graphical program;*

Figure 3.5: *The studied simplified system and the list of its elements;*

Figure 3.6: *Interactions of the Element 1;*

Figure 3.7: *Interactions of elements, excluding self-interactions;*

Figure 3.8: *Matrix of interaction;*

Figure 3.9: *Graphical representation of functions in the simplified model;*

Figure 3.10: *Matrix of functions;*

Figure 3.11: *Function diagram of the studied system;*

Figure 3.12: *A three-dimensional studied model;*

Figure 3.13: *A three-dimensional studied model with coordinates;*

Figure 3.14: *Blocks of elements placement;*

Figure 3.15: *Defining direction of an arrow and its graphical representation;*

Figure 3.16: *Final function diagram of the studied system;*

Figure 3.17: *The system for ranging of elements;*

Figure 3.18: *The studied system after trimming;*

Figure 4.1: *Experience in the field of building structures design among the respondents;*

Figure 4.2: *Distribution of areas of activities among the respondents;*

Figure 4.3: *Regularity of using graphical programming tools among the respondents;*

Figure 4.4: *The respondents` attitude regarding such a proposed software feature as giving ready prompts from a database of proven solutions;*

Figure 4.5: *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;*

Figure 4.6: *The respondents` attitude regarding such a proposed software feature as giving clues for finding non-trivial solutions that are not common in construction design;*

Figure 4.7: *The respondents` attitude to demonstrated functionality of the proposed approach;*

Figure 4.8: *The respondents` attitude regarding probability of possible improvements that may be achieved applying functionality of the proposed approach;*

Figure 4.9: *The proposed approach`s functions that are found to be the most useful and applicable by the respondents;*

Figure 4.10: *General evaluation of a novel approach for automated conceptual design of building structures;*

Figure 4.11: *Experimental model. (a) Physical, (b) Analytical;*

Figure 4.12: *Interaction matrix of the experimental model;*

Figure 4.13: *Function matrix of the experimental model (only harmful functions are shown);*

Figure 4.14: *Function diagram of the experimental model;*

Figure 4.15: *Highlighting elements after ranking;*

Figure 5.1: *Interconnections between the publications.*

List of tables

Table 1.1: *Research questions in the thesis structure;*

Table 3.1: *Tabular representation of the interaction matrix;*

Table 3.2: *The table of functions;*

Table 3.3: *Defining functions by categories of elements;*

Table 3.4: *Location of Z coordinates of different categories of elements;*

Table 3.5: *Direction of interaction;*

Table 3.6: *Grouping by the coordinate Z;*

Table 3.7: *Results of ranking;*

Table 3.8: *Trimming report;*

Table 3.9: *The Construction Contradiction Matrix;*

Table 4.1: *Ranking results;*

Table 4.2: *Trimming report;*

Table 5.1: *Summary of the publications included in the thesis.*

List of abbreviations

AEC	Architecture, Engineering and Construction;
AHP	Analytic Hierarchy Process;
BIM	Building Information Modelling;
CAD	Computer-Aided Design;
CAI	Computer-Aided Invention;
CCM	Construction Contradiction Matrix;
CD	Conceptual Design;
CPM	Construction Project Management;
CPMBOK	Construction Project Management Body of Knowledge;
DD	Detailed Design;
DM	Data Mining;
DSDI	Define, Solve, Design, Implement;
ETRIA	European TRIZ association;
GCPM	General Construction Problem-Solving Model;
IFR	Ideal Final Result;
IT	Information Technology;
KMS	Knowledge Management System;
MAGIA	Model for Automated Generation of Innovative Alternatives;
MEP	Mechanical, Engineering and Piping;
MEPS	Model of Engineering Problem Solver;
MHBMO	Modified Honey Bee Mating Optimization;
MP	Management Parameters;
MUGICA	Model Used for the Generation of Innovative Construction Alternatives;
NIMBS	National Building Information Model Standard Project Committee;
PSP	Problem-Solving Principles;

QFD	Quality Function Deployment;
RC	Reinforced Concrete;
RQ	Research question;
SoA	Step of Automation.
STIP	Systematic Technology Innovation Procedure;
TAM	Technology Acceptance Method;
TRIZ	Theory of Inventive Problem Solving;
VE	Value Engineering;

1 Introduction

1.1 Research background

Construction engineering is the professional discipline within building industry which deals with design, overall planning and construction of infrastructures (buildings, bridges, utilities, etc.). To succeed in those aspects construction specialists must always find new solutions and ideas, solve technical and technological issues which may appear at every single project's stage during both design and construction. Thanks to bright innovative ideas and solutions, which enable the scientists and engineers to evolve construction materials, technologies, design techniques, etc., the World nowadays has such truly astonishing structures as the Dubai's Burj Khalifa (the tallest man-made structure in the world, standing at 829,8 m), the Sidu River Bridge in China (the bridge with the biggest drop distance from the bridge deck to the ground level which is nearly 500m high and crosses a mountain belt), the incredible Milau Viaduct in France (the world's tallest bridge with one mast reaching 343 meters above the base of the structure), the China's Jinping-I Dam (the tallest dam 305m high), the Capital Gate tower (the World's furthest leaning skyscraper in Abu Dhabi that was built to lean 18°) and a few others. Moreover, there are quite simple structures differing by the way they were built. For instance, a Chinese construction company used a Modular method and became the world's fastest builder after erecting a 57-storey skyscraper in 19 working days in central China (Changsha 2015). The method enabled the builders to assemble the prefabricated blocks (modules) instead of building brick by brick.

In the modern professional world engineers must have a multiple-purpose intellectual set of tools that would enable them to find the right ideas in a well-structured methodological way avoiding consideration of knowingly false solutions leading to waste of time, missed deadlines and planned budgets, etc. Since the risk of failure in construction is higher than in many other industries (Kulatunga et al. 2006) it is not acceptable to use trial-and-error approach (especially for large-scale projects) to find ideas and solutions for the development and improvement of design procedures, structures and construction techniques.

1.1.1 Early design stage in construction

Early design stage in Architectural and Construction projects is a crucial part of sophisticated long-term design process. This stage is also known as Conceptual Design (CD) and many fundamental and critical solutions are taken into account here. The smarter and less trivial solutions are developed during the CD, the more advanced, effective, and less costly design is gained. Those solutions can be found by using different techniques of ideas generation, such as morphological charts, synectics, brainstorming, TRIZ tools, etc. TRIZ is believed to be one of the most effective and well-structured problem-solving techniques. The first publication describing its principles was published in Russian in 1956 (Genrich Saulovich Altshuller and Rafael

Borisovich Shapiro 1956). In English nowadays one of the most popular thematic materials is the work by Salamatov (Salamatov 2005). TRIZ is well applicable to architecture and construction (Coşkuna; Altun 2013; Altun 2011; Chiu & Cheng 2012; Shao-tsai Cheng, Wen-der Yu, Chih-ming Wu 2009; Conall Ó Catháin 2009; Lee & Shin 2014; Mohamed & AbouRizk 2005; Teplitskiy 2005b; Teplitskiy 2005a; Teplitskiy 2005c; Lin & Lee 2005). In our digital century it is reasonable to link modern construction design software with ideas generation techniques in order to enhance and automate design creativity. Nowadays Building Information Modelling (BIM) became popular stream in construction design. Existing BIM software have range of instruments enabling designers to bring all their knowledge and experience into projects but, however, such software does not support users in searching for nontrivial conceptual ideas for design. That is why the ideas generation stage is still a separate, not automated and human-depended part of construction design.

1.1.2 Building Information Modelling

The US National Building Information Model Standard Project Committee has the following definition (NIMBS Committee 2007): “Building Information Modelling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from the earliest conception to demolition”. Despite all BIM advantages comparing to 2D CAD design it has no solutions helping designers in automation of conceptual design stage. According to the latest data (Faber, Jaron, et al. 2016) Autodesk Revit® was determined as a leader among the best BIM software products by customer satisfaction (based on user reviews) and scale (based on market share, vendor size, and social impact). Autodesk Revit® is a building information modelling software for architects, structural engineers, MEP engineers, designers and contractors. It allows users to design buildings and structures and its components in 3D, annotate the model with 2D drafting elements, and access building information from the building model's database. Revit® is 4D BIM capable with tools to plan and track various stages in the building's lifecycle, from concept to construction and later demolition. Based on above, Autodesk Revit® was selected by the author as the basic and most promising software for realization of a proposal for conceptual design stage automation in AEC projects. Moreover, this is the only software that has a built-in open source graphical programming tool for design, which extends building information modelling with the data and logic environment of a graphical algorithm editor and enables users to significantly expand functionality of the software without having special knowledge of programming. The tool is called Dynamo® (DynamoBIM, n.d.).

1.1.3 Theory of Inventive Problem Solving

"TRIZ" is the Russian acronym for the "Theory of Inventive Problem Solving." G.S. Altshuller and his colleagues in the USSR developed the method between 1946 and

1985. TRIZ includes a practical methodology, tool sets, a knowledge base, and model-based technology for generating innovative solutions for problem solving. The approach includes a number of tools, some of the most used are the Ideal Final Result and Ideality; Function Modelling, Analysis and Trimming; the 40 Inventive Principles of Problem Solving; Trends of Technical Systems Evolution and Technology Forecasting; 76 Standard Solutions. The method is quite universal and finds its application in different fields. During last decade, there were a number of attempts to apply TRIZ to also non-technical areas such as business, service, art, etc. Among them quite popular works (Gazem & Rahman 2014; Hsuan-Tzu Hsu 2013; Retseptor 2005; Yang 2013).

Ding and Ma (Ding & Ma 2014) report that using the Theory of Inventive Problem Solving can accelerate technical innovations in construction process. On the other side, the report by Cavallucci (Cavallucci 2009) shows the statistical data related to distribution of TRIZ usage in industrial sectors (see Figure.1.1). According to the ETRIA (the European TRIZ association) Worldwide survey performed in 2009, only 3,5% of construction professionals are devoted to the TRIZ, which means that **TRIZ remains marginal in the building industry.**

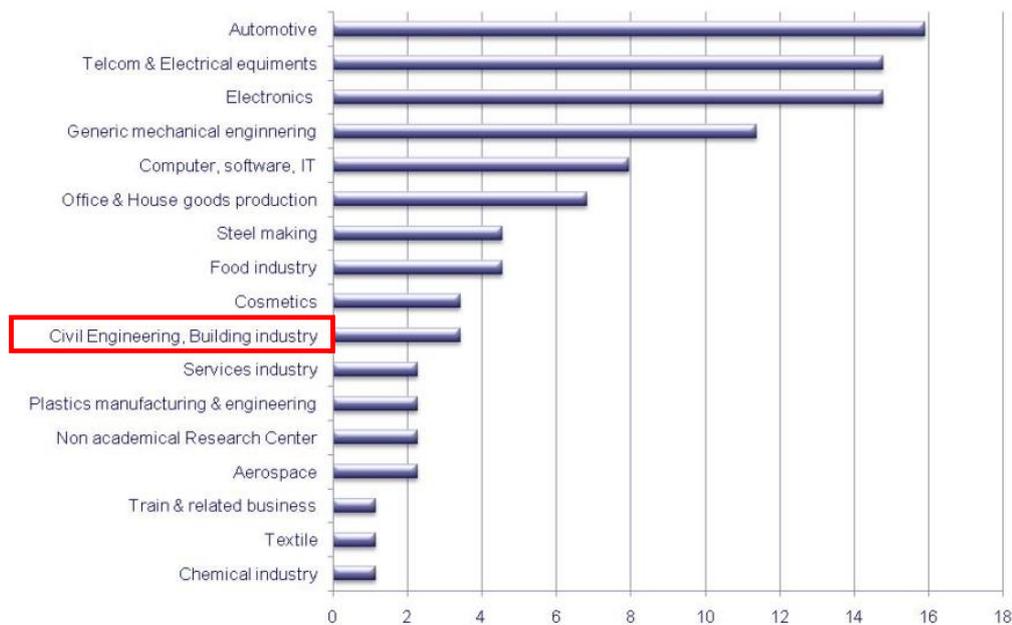


Figure 1.1: Distribution of TRIZ tools usage in industrial sectors (Cavallucci 2009)

Conall Ó Catháin (Conall Ó Catháin 2009) explains again that construction specialists in most cases do not use systematic or formal design methods which leads to a number of drawbacks (for instance, it takes long time to find a solution; waiting for

inspirations; designers cannot proceed in a logical manner, etc.). To avoid such cons, it is suggested to use a systematic inventive approach which came out of TRIZ.

Furthermore, Mohammed (Mohamed 2002) mentioned that there is lack of structured theory for managing innovation improvement in the construction industry. Innovation is an integral part in improvement of construction techniques but, however, most approaches are based on the trial-and-error method. The research presents few numbers of case studies to show satisfaction results of TRIZ application in tunnel construction. All case studies were taken from real life situations and it was well proven that TRIZ tools help to achieve innovation conceptual solution in a methodological way avoiding consideration of irrelevant results.

Ding and Jiang (Ding Z., Jiang S. 2013) particularly propose the design framework of the technology innovation platform based on TRIZ by taking advantage of available patent knowledge in the construction industry. Based on extracted construction patent knowledge, the development of construction technology innovation platform enables a heuristic environment to help the industry improve the innovation capacity and efficiency by motivating knowledge worker's innovative thinking.

The most significant review on the degree of application of TRIZ in different areas is made by Leonid Chechurin (Chechurin 2016) and (Chechurin & Borgianni 2016). Those works also confirm that TRIZ may be used in construction but still not widely applicable.

1.2 Research objectives and research questions

Currently, the level of automation in construction design remains rather low, however, in the digital era there are many possibilities to increase it. Nowadays the Building Information modelling technology received significant development, and its integration with existing tools of ideas generation can have remarkable potential. Additionally, such an effective instrument for inventive problem solving as TRIZ still has low level of use in building industry. After successful integration into the construction software its application will increase significantly. In many cases, this will happen even unconsciously, because the designers will only use the ready-made functionality of the program.

The research answers the following consistent research questions (RQ):

RQ1: To what extent the inventive problem solving techniques are used in the construction field?

RQ2: To what extent is it relevant to develop a new approach for the conceptual design stage automation and what tools can be used for supporting automation of the conceptual design in construction?

RQ3: *What features of the new method can ensure its wide application?*

The chosen research questions are interdependent. Together they address the dissertation objectives listed below.

Research hypothesis: *Application of TRIZ tools at early design stage in construction will lead to more effective building information models requiring less changes during further stages of design.*

1.3 Focus of the thesis

The focus of the research can be illustrated as an intersection of the following fields: Conceptual design in construction (CD), Building information modelling (BIM), Theory of inventive problem solving (TRIZ) and Computer-aided invention (CAI) (see Figure 1.2).

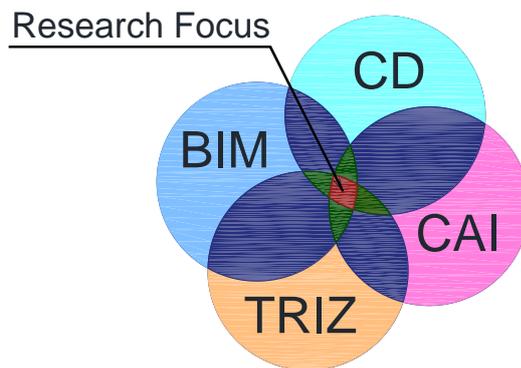


Figure 1.2: Euler diagram showing the research focus

The literature search has not identified professional construction software which would automate the early design process in terms of searching for not only optimal and reliable solutions but also for inventive ones. On the other hand, Building Information Modelling and graphical programming for design are state-of-the art in modern construction design and Computer-Aided-Invention software is becoming more popular in different disciplines. Merging all above mentioned with existing inventive techniques could add artificial intelligence into AEC design software and enhance and automate design creativity in conceptual design stage. Result of the research is a novel methodology based on the integration of features from TRIZ and CAI into BIM software in order to enhance automation of the conceptual design stage in construction.

This research has several principal goals which are:

- I. **Scientific goal** focuses on developing a Design Methodology of the structural systems conceptual design;
- II. **Economic goal** focuses on reducing time and cost of conceptual design and, hence, further detailed design and construction;
- III. **Technical goal** focuses on proposal and realization of technical solutions for the developed design methodology and linking it with modern software for construction design.

To achieve the above mentioned principal goals, the following objectives was set in the research:

- 1) To review the literature in the scope of the research;
- 2) To determine leading BIM software;
- 3) To review TRIZ tools and choose the most suitable for application in the construction design;
- 4) To develop the sequence of TRIZ tools application for the conceptual design methodology;
- 5) To develop the sequence of actions inside each level of the developed methodology;
- 6) To create an experimental model for testing the conceptual design methodology;
- 7) To propose a technical solution for automation of the developed algorithm;
- 8) To validate results by testing the algorithm with professional designers.

1.4 Structure of the thesis

This thesis consists of two sections. Section I presents an overview of the study, while Section II is a collection of the individual publications that present the results of the research process. Section I is divided into 6 chapters. Chapter 1 is the introduction on the topic, it explains the research background and sets research objectives and research questions. Chapter 2 is the literature review. It discovers state of the art in the research field. Chapter 3 is the main part where the model of the proposed method has been developed. Chapter 4 presents evaluation results of the proposed approach and provides a case study. Chapter 5 is the summary of the publications. Chapter 6 provides the conclusions, discusses the application and limitations of the results as well as possible further research directions.

Table 1.1 illustrates the connection and the contribution of the chapters and the included publications towards the research questions.

Table 1.1: Research questions in the thesis structure

Thesis chapters	RQ1	RQ2	RQ3
1. Introduction			
2. State of the art			
3. Model development			
4. Results			
5. Summary of the publications			
5.1. Publication I			
5.2. Publication II			
5.3. Publication III			
5.4. Publication IV			
6. Discussion and conclusions			

Publication I is dedicated to literature review on general application of TRIZ in the construction field. Publication II presents the main idea of the proposed methodology and a case study of its practical implementation. Publication III describes the logic for TRIZ tools integration into the chosen software. Publication IV focuses on evaluation of the developed technique.

2 State of the art

2.1 Demand of innovation in construction

First, we would like to comment on demand of innovation in the construction industry in general. For that purpose we have analysed some of the most cited publications in this field. According to Dale (Dale 2007) innovation can be defined as “the successful exploitation of new ideas” or, in more practical way, it makes sense to talk about innovations in construction when new technologies, techniques, structures, materials, etc. were successfully introduced into industry, in particular case in the building industry, and applied in specific projects. However, ongoing research (Kulatunga et al. 2006; Blayse & Manley 2004; Ding Z., Jiang S. 2013; Asad et al. n.d.; Ozorhon et al. 2010) and statistical data (Cavallucci 2009; Dale 2007) show that construction lags behind many other industrial sectors (such as IT, computers, software, automotive industry, electronics, mechanical engineering, etc.) in terms of efficiency and productivity due to mostly lack of realizations of new ideas.

For instance, Kulatunga et al. (Kulatunga et al. 2006) demonstrate that construction is behind other industrial sectors due to, in particular, lack of innovations. At the same time modern construction companies are keen on innovations to be competitive on the market, which is why engineers and managers innovate when technology can be modified easily. On the other hand, construction industry is also known for its conservatism and professionals tend to use an accepted industry practice and norms in fulfilling client’s need.

Asad et al. (Asad et al. n.d.) also show importance of innovations for construction organizations. The authors even claim that construction innovations can become a fourth dimension in the future along with the traditional dimensions of cost, quality and time. Only in that case such organizations would be able to take advantages of changes in market economy. Toole (Toole 2001) additionally explains that successful building products must be innovative to become competitive on the market in terms of cost, time and performance efficiency.

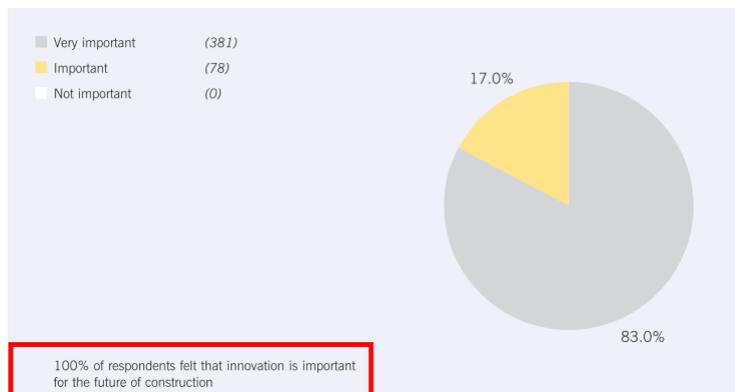


Figure 2.1: Importance of innovations for the future of construction (Dale 2007)

Besides, the survey performed by the Chartered Institute of Building (UK) (Dale 2007) discovered that 100% of respondents felt that innovation is important for the future of construction (see Figure 2.1).

Therefore, it seems quite logical to conclude that innovations must be on demand in the construction industry but, at the same time, the construction industry is considered slower in technology innovation in the past decades partially due to the characteristics of the industry.

To sum up there are enough researches, surveys and literature regarding innovation in construction and almost all of them prove that innovations are vital in construction sector but another question is "how to become innovative". The answer is given further.

2.2 Application of TRIZ in construction

The literature review on application of TRIZ in the construction field is based on papers indexed by the SCOPUS mostly database. In order to create the set of articles to be reviewed, two searches were performed: (1) the search query "TRIZ" and "Construction" in Title or Abstract or Keywords and (2) "TRIZ" and "Building" in Title or Abstract or Keywords. The terms "Construction" and "Building" were selected as they are most commonly used in the studied field while "TRIZ" as generally accepted abbreviation for the Theory of Inventive Problem Solving. The former case resulted in 116 papers while the latter in 81 ones. However, reading the papers filtered out the irrelevant texts that reduced the quantity significantly to only 18 and 6 industry-related articles respectively with 2 of them being in both lists. Thus, the dataset consists of 22 articles selected from the SCOPUS database. It is just around 1% of the 2124 articles retrieved by "TRIZ" in Title or Abstract or Keywords search. Quick analysis shows that 9 of articles are cited more than once. Most of the works originated from the PRC during the last decade. As the amount of retrieved papers is very small, the Google finder was used to extend the list of reviewed papers. The search query "TRIZ" and

“Construction” and “Building” forwarded us to such sources as Science Direct, Elsevier and Springer where 6 more industry-related papers were obtained. All bibliographic information is given as it was seen in October 2018. Thus, 28 works regarding application of TRIZ in construction were discovered and reviewed, some of which are available in abstracts only. The review shows that those articles are mostly dedicated to:

- Development of Construction Technologies;
- Design of New Structures and Construction Materials;
- Construction Project Management and Value Engineering.

2.2.1 Development of construction technologies

A small amount of research has been done regarding development of construction techniques and technologies using TRIZ. For instance, the researchers (Shao-tsai Cheng, Wen-der Yu, Chih-ming Wu 2009) describe step-by-step analysis of formwork technology development from the TRIZ point of view. The 40 inventive principles are used for formwork patents investigation. Based on 176 Taiwan patents analysis from years 1975 to 2005 there were extracted top 5 inventive principles which were most frequently used in the formwork patents. The principles are: (1) prior action, (2) Combining, (3) Segmentation, (4) Cushion in advance and (5) Mediator. Some examples of each of them are given in the work to show the formwork technology development. To predict future development trends, the contradiction matrix was used, which led to determination of future innovation trends of formwork engineering. Among those trends are the following inventive principles: Inversion, Segmentation, Transformation of properties, Replacement of mechanical system and Extraction. Finally, it was concluded that TRIZ provides a systematic approach for technology research, and construction technologies can be analysed with TRIZ.

Yu in the works (Yu et al. 2008) and (Yu W.-D., Wu C.-M. 2009) also states that construction technologies are little comparable to other industries due to lack of innovation tools. They proposed to use a Systematic Technology Innovation Procedure (STIP) for fast innovation in construction technologies. The STIP approach is also based on patent analysis, TRIZ and Computer Aided Invention (CAI) tools. STIP consist of (1) a problem description scheme, (2) a systematic procedure of technology innovation and (3) a set of criteria for technology evaluation. STIP principal scheme is: PROBLEM → DEFINITION → ANALYSIS → SOLUTION (using TRIZ) → APPROVAL → INNOVATIVE TECHNOLOGY. A case study of STIP application in searching an innovative solution for leaking pipes surrounded with reinforced concrete (RC) is provided as an example.

Furthermore, the same authors developed their research (Wu et al. n.d.). They explained that technology innovation has been an important source of competitiveness for individual construction firms and provide long term benefits for the industry. In this

research they proposed a new integrative “Model Used for the Generation of Innovative Construction Alternatives” (MUGICA) based on the formerly developed STIP and the “Model for Automated Generation of Innovative Alternatives” (MAGIA) to tackle both the systematic and automated requirements of construction technology innovation. The testing result showed that the proposed MUGICA was able to improve both the efficiency and effectiveness of construction technology innovation compared to previous approaches.

According to a popular research (Kevser Coşkuna; Altun 2013) in-situ construction techniques have distinct characteristics such as unique production, partial lack of industrialization, standardization and quality control, location of construction process, local techniques related to construction culture. Those characteristics are mostly reducing “productivity”. There are several innovation models for improving the “quality” in the construction process. The authors found out that TRIZ could be used to improve the quality of in-situ construction techniques. However, it was discovered that improvements are needed to the “analysis of the problem” and “evaluating proposed solutions” steps of the TRIZ approach. According to the comprehensive investigation of other improvement methods, the Six Sigma approach was found to be effective in overcoming the uncertainties in TRIZ. In the paper a conceptual model for improving in-situ construction techniques is proposed by using the TRIZ approach, the Six Sigma approach and statistical tools. It was demonstrated that the integration of TRIZ and Six Sigma approaches is considerably more effective. The same authors also investigated the applicability of the TRIZ tools on in-situ construction technologies (Kevser Coşkuna; Altun 2011). Improving the quality of the construction technique for wood joint fixing is defined as a problem to be tackled. The problem was solved with TRIZ method considering "construction time" and "strength" criteria. For the assessment of the method, construction process observation and compressive strength tests were carried out.

Lin (Y.H. Lin 2005) presented a modified TRIZ model called TRIZ-AHP-G model which combines with Analytic Hierarchy Process (AHP) and grey relational analysis. The use of TRIZ-AHP-G model was illustrated by two examples, the pre-stressed concrete and the shoring system. The results of both examples demonstrated the effectiveness of this proposed model, which can effectively measure the importance of criteria associated with innovating products based on expert knowledge.

2.2.2 Design of new structures and construction materials

TRIZ has also shown its potential in design of new structures and construction materials. One of such examples is an integrated innovation method combining TRIZ, Technology Acceptance Method (TAM-approach for product demand analysis) and Quality Function Deployment (QFD - transforms customer or market demands into design requirements) suggested in the work by Luo et al. (Luo et al. 2012). The approach helps to solve main contradiction problems from the product demand analysis to its design, production and application. An example for design of new wall material

using integrated method was given in the paper. The core part of the method is identification and solving contradictions in customer demand and quality control during design and production procedures using different TRIZ tools. As for building façade solutions, a team of scholars (Chen, Z., et al. 2006) proposed a TRIZ based management process model for selecting the most appropriate solutions of building façades. To set up the model, environmental values of building facades were analysed with respect to their life-cycle performance and impacts.

Besides that, TRIZ can be applied in finding inventive ways to upgrade heat insulation of external building structures. Chiu and Cheng (Chiu & Cheng 2012) describe how solar reflectance of heat-proof paint was improved by applying TRIZ contradiction. The parameters which were discovered to be improved are the following: temperature, harmful elements on objects, adaptability, stability of objects and brightness. To solve those five contradictions, four inventive principles (transformation of the physical and chemical states of an object, segmentation, changing the colour and flexible membranes or thin film) were singled out in TRIZ. A number of heat resistance tests were performed, which led to successful development of new paint that upgrades the solar reflectance and heat insulation of the plate paint and, thus, saves over 24% of electricity for internal air conditioning.

The other study by Lee and Shin (Lee & Shin 2014) shows how TRIZ can be used when it is required to evaluate bearing steel diagrid structures of free-shaped tall buildings to resolve such issues as the concentration of stress at the ends of the tube contacted to cap plates. Stress concentrations among node rib, cap plate and tube result in collapses of tubes before tubes arrive to yielding stress state. This occurs despite using cap plates, like as changing thickness and extended length. In addition, an extended cap plate may cause interference in building construction. In this study a DSDI TRIZ procedure was mainly applied in order to develop the details of diagrid structures. The DSDI (for “Define”, “Solve”, “Design”, and “Implement”) approach was introduced by a POSCO steel company in 2008 (TRIZ Research Team 2009). In the “Define” stage it is required to define the above-mentioned problem of the existing diagrid detail. It was found that stresses by high performance steel tube with tensile stress of 800 MPa have to be bigger than stresses by given forces at the zone of the tube in which the tube contacts the cap plate in order to avoid collapse. Inventive ideas were evaluated by solving the problem that exists in the operating zone. Since the diameter and thickness of each tube are constant for the purpose of economy, they could not be considered to be design variables in the operating zone. Cap plate and node rib are design variables and can be modified to improve the existing diagrid details. To solve the problem and generate inventive ideas the authors considered a multi-screen thinking method, a resource analysis and interaction matrix. To resolve technical and physical contradictions, separation in space and based upon condition were applied to idea generation. As a result, the cap plate was modified to both enlarge the contact area between a tube and a cap plate and reduce the interference that results from length extensions of a cap plate. Therefore, original flat cap plates were developed to be either concave or convex shaped plates. The “Design and Implement” stages of DSDI TRIZ procedures measure the idea

generation results by using measurable tools such as structural analyses or experiments. In the particular case the researchers applied ABAQUS to investigate structural behaviours of the invention results. A convex diagrid was evaluated as being an improvement on the current best solution. TRIZ applications shown in this study verify that TRIZ is a strong idea generation tool for conceptual design to improve current steel-framed products such as diagrid structures in tall buildings. Another research related to TRIZ usage in steel bearing structures design was presented by Lee (Lee D. 2015) where they suggested developing an advance in the frame modules and frame structures used to truss structures. The DSDI approach was also used to verify that the advanced product secures structural safety and is of optimized size.

Craig (Craig et al. 2008) suggested applying so-called BioTRIZ approach for radiative cooling of buildings. BioTRIZ is a combination of TRIZ and Biomimetics - methodology for using Principles of Nature in problem solving and design. BioTRIZ matrix was applied in order to design roofs for buildings in hot climates that get free cooling through radiant coupling with the sky. The chosen solution is to replace the standard insulation component with an open cell honeycomb. The vertical cells allow longwave radiation to pass, while stopping convection.

2.2.3 Construction project management and value engineering

The key target of Construction Project Management (CPM) is satisfaction of a customer, codes and regulations to deliver a qualitative, safe, secure and financially effective project that meets the designed time schedule and budget. Hence, in order to achieve those goals specialists have been applying various techniques to managing a complex construction process. Since the level of competitiveness and complication of projects have been increasing, the majority of such techniques cannot be considered beneficial nowadays. Several papers were discovered during literature review regarding the above-mentioned subtopic. For instance, Cabrera and Li (Cabrera & Li 2014) suggest more effective construction process via application the key TRIZ tool such as the contradiction matrix in order to develop innovative solutions to the most complex issues. As a practical example, the case study based on application of TRIZ tools in a highway construction was discussed. The above-mentioned tools assist optimization of working method for soil grading and compacting. However, the authors noticed that the innovative solution, after some time of testing, would possibly create new issues which should be further re-evaluated with help of TRIZ techniques and common practice. Moreover, the authors concluded that all project's participants have to always accurately investigate and discuss created inventive solutions before applying them into practice. Cui (Cui 2014) presented conflict resolution methods for construction projects from the standpoint of TRIZ. Based on the review of the article abstract, the main TRIZ tools used were: the ideal final result (IFR), Substance-Field (Su-Field) analysis, 76 standards, separation principles, contradiction matrix and 40 inventive principles. Case studies of key conflicts limiting the IFR were discussed in details. Additionally, a few specific solutions for the physical and technical contradictions in the construction

projects were presented with the illustration of conflict resolutions as a case. Chang et al. (Chang, P.-L., et al. 2010) developed and tested a preliminary Model of Engineering Problem Solver (MEPS) based on TRIZ to explore the underlying patterns of problem solving for emergent construction problems. MEPS consists of 15 identified management parameters, a contradiction matrix and 16 problem-solving principles. Their work received further development in a popular research (Chang, P.-L., et al. 2012) where a General Construction Problem-Solving Model (GCPM) was presented. The proposed GCPM integrates Construction Project Management Body of Knowledge (CPMBOK), TRIZ and Data Mining (DM), so that the management parameters (MP) and Problem-Solving Principles (PSP) are defined and derived. The model is to assist the construction engineers in solving various emergent problems they encounter daily.

Along with amelioration of conflict resolution methods for construction projects using TRIZ, a number of steps towards improvement of value engineering (VE) in construction were taken as well. One of such attempts was, for instance, performed by Zhang et al. (Zhang et al. 2009). The paper presents a value engineering knowledge management system (VE-KMS), which applies TRIZ and integrates its tools into the creativity phase of the VE process and, hence, makes the creativity phase more systematic, organized and problem-focused. Procedures of the improved VE creativity phase consist of the following steps: (1) collect project explicit knowledge and VE team information, (2) break project into subsystems, (3) identify harmful functions in each subsystem Function (using TRIZ function analysis), (4) identify and solve technical contradictions (the TRIZ contradiction matrix), (5) identify and solve physical contradictions (four general separation principles to solve physical contradictions: (a) separation in time, (b) separation in space, (c) separation between the whole system and its parts, and (d) separation based on different conditions), (6) conduct substance-field analysis, (7) improve the project according to technological evolution trends (using TRIZ nine evolution patterns). The direction regarding value engineering in construction was developed by the same scientists in their following work (Mao et al. 2009) where they explored the possibility of incorporating TRIZ into the workshop session of the value engineering exercise by initiating three new procedures in this session: (1) an initial design procedure to examine the functions of a proposed project; (2) a function trimming procedure to fully utilize existing resources and ensure low life-cycle cost and sustainability of the proposed project; and (3) an interaction analysis procedure to assess the proposed project in a broad perspective with social, economic, and environmental awareness. The objective of the following paper by Yang et al. (Yang et al. 2014) is to investigate the characteristics of contradiction in idea creation, and use them to create better design alternatives in construction VE. An Idea Breakdown Structure (IBS) was applied as the principle of problem solving. Ding and Wang (Ding, Z., Wang, J. 2012) developed a "TRIZ and patent laboratory" (TP Lab) platform to promote innovations and manage the knowledge in the construction industry where TRIZ was applied in order to extract available patent knowledge.

2.3 Automation of conceptual design in construction

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 3600 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 1095 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 was 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 analysing 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. The information is given as it was obtained in October 2018.

The review of the retrieved literature shows that linking engineering design software with ideas generation techniques and development of CAI (Computer-Aided-Invention) systems is still a new research topic. In the work by Ikoenko (Ikoenko 2004) it was mentioned that merging TRIZ with other methods gave birth to several integrated methodologies based on TRIZ and it opened new horizons for CAI development to cover all the parts of those methods, both analytical and concept generating. Also Bakker and Chechurin et al. (Bakker et al. 2011), (Chechurin et al. 2011) explained a link that was missing between CAI and CAD (Computer-Aided Design) software. Furthermore, the authors proposed integration of CAI and CAD software. Also León-Rovira (León-Rovira 2001) suggested to integrate TRIZ and CAD in order to increase design effectiveness and productivity. Also the review of existing literature in the field of architecture and construction showed that new technological advancements in AEC design have brought the “level of automation” as a pivotal factor in the success of projects. In the article by Abrishami et al. (Abrishami et al. 2014) it is shown that extant literature has identified a significant knowledge gap concerning the key impact links and support mechanisms needed to overtly exploit computational design methods, especially BIM, throughout the conceptual design stage. Moreover, most of the respondents studied in the paper highlighted several deficiencies in the existing tools, whilst they asserted that such a purposeful BIM interface can offer comprehensive

support for automation of the entire of AEC design and implementation phases, and particularly enhance the decision-making process at early design phases.

Detailed review of the discovered literature showed that automation of design for construction is still a relevant topic and building information modelling is one of its key drivers. For instance, in the highly cited paper (Becerik-Gerber & Kensek 2010) 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 (Yalcinkaya & Singh 2015). 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 modelling and design” and “BIM-supported structural analysis and design” are among them. According to the survey performed by Abrishami et al. (Abrishami et al. 2014) 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 (Robertson & Radcliffe 2009) regarding computer-aided design (CAD) 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 trialling 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 the research by Yu et al. (Yu et al. 2012) the function modelling 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 also found its implementation in Building Information Modelling in construction (Sacks et al. 2010). Such synergy could improve construction design processes.

Bernal et al. (Bernal et al. 2015) 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 a research team lead by Książek (Książek et al. 2015), 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 analysed by a number of scholars. For instance, Østergård (Østergård et al. 2017) concluded that most of the 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 by Petersen and Svendsen (Petersen & Svendsen 2010) 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 may help to integrate decision-making tools into either BIM or CAD software. According to Nembrini et al. (Nembrini et al. 2014) 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 (Negendahl 2015) 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 (Paul & Borrmann 2009) 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 (Brown & Mueller 2016) suggested using geometric multi-objective optimization for design for structural and energy performance of long span buildings. Fenton et al. (Fenton et al. 2014) developed an approach for using grammatical evolution for automatic innovative truss design. Laefer and Truong-Hong (Laefer & Truong-Hong 2017) have concentrated on automatic generation of 3D steel structures for building information modelling. Afzali et al. (Afzali et al. 2016) developed a procedure based on the Modified Honey Bee Mating Optimization (MHBMO) 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. (Song et al. 2012) where the authors 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 (Tuhus-Dubrow & Krarti 2010) 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. Nimitawat and Nanakorn (Nimitawat & Nanakorn 2009) 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. (Kwon et al. 2009) developed a novel principle of shape generation.

We would also like to mention that significant attention is put on automation of mechanical systems conceptual design by integrating such CAD software as Solid Works© and TRIZ tools. Ongoing research is being performed in the Lappeenranta-Lahti University of Technology LUT by Nikolai Efimov-Soini (Efimov-Soini & Chechurin 2017) who is also works on general development of TRIZ tools. The most cited works in this field are, for instance, (Efimov-Soini & Chechurin 2016; Efimov-Soini, Chechurin, et al. 2016; Efimov-Soini & Uzhegov 2017; Efimov-Soini, Kozlova, et al. 2016).

Moreover, an approach to an integration of TRIZ and heuristic methods for the development of industrial products was developed by Dr. Francesco Rosa (Rosa et al. 2006), who also suggested embedding biological knowledge in a conceptual design tool in cooperation with Niccolò Becattini and Getano Cascini (Becattini et al. 2016) and unified ontology for causal-function modelling in biologically inspired design (Rosa et al. 2015). Biomimetics is a promising trend nowadays and also may be considered for conceptual design support in construction industry.

2.4 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 Building Information Modelling. 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.

3 Model development

As a brief introduction to the chapter we, first, provide a short description of the developed method. In this approach software is supposed to self-analyse the Building Information Model and suggest solutions in order to improve the system. For that purpose, it is suggested to use the TRIZ Function Modelling and rules of trimming. In order to teach software to extract a function model from BIM model, a special script has been built with help of Dynamo®. The script, first, automatically detects elements/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. On the next step the software defines functions of elements in the Interaction Matrix. In building structures, in relation to external loads, those functions are usually “holds (or supports/bears)”. However, such functions among the elements themselves, as “bends”, “expands”, “compresses”, “twists” etc. may take place. We call those functions harmful since ideally the structure has to carry the load without any internal stresses. For identification of interactions the script also applies special 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 on elements and functions. Also, the software helps to achieve a more complete and convenient workflow for design engineers as all is done within the BIM environment. Finally, having this overview is a prerequisite for performing 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 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 design engineer can accept other decline those proposals. In function ranking functions of elements are ranked by their level of usefulness. In order to perform ranking we, first, have to identify a “target function” (for instance, “carry live load”). The higher 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 co-called “harmful functions” and it may be necessary to eliminate such functions if it is demanded to design cheaper but 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 analyse the Building Information Model (BIM model) and easily obtain nontrivial design avoiding complex processes of topology optimization and structural analysis which are issues for further detailed design. As a case study we analyse a simple beam structural system.

Further the method is described in details. In the thesis it is suggested to introduce computer-aided automation of searching for new ideas and nontrivial solutions during conceptual design in construction in order to simplify and automate complex decision-making process at early design stages. We propose to apply three steps for conceptual design support in construction. Let us call them Steps of Automation: (SoA1), (SoA2) and (SoA3). Step 1 is not supposed to use any problem-solving techniques, hence, it is more about creating a preliminary BIM model but still has significant meaning for design process. Here graphical programming for design (Dynamo®) and extended build-in databases of optimal and well-tested design solutions are tools to be used. However, standard functionality of existing software may also be used for building a BIM model. In the Step 2 software is supposed to self-analyse Building Information Model and suggest solutions in order to improve the system. For that purpose, the TRIZ Function Modelling and trimming are used. In the Step 3 software users receive more inventive prompts in a semi-automated way. Here it is suggested to implant the TRIZ Contradiction Matrix into software. In this case users formulate technical contradictions and automatically gain inventive principles and examples on how those contradictions can be solved. Further and final design solutions are up to engineers.

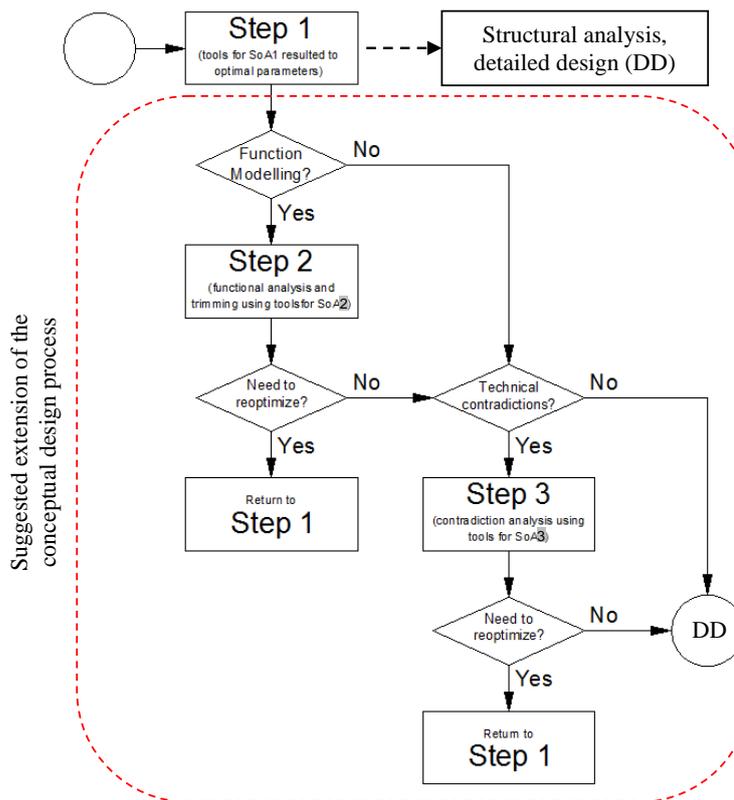


Figure 3.1: Roadmap of the conceptual design process

SoA1 is a standard existing procedure, SoA2 is optimisation of the BIM model (optimal solution), and SoA3 is search for nonstandard solutions (inventive solutions). SoA2 and SoA3 are proposed in this research to be added to the roadmap of conceptual design process. The suggested conceptual design process scheme is shown in the Figure 3.1. This process precedes structural analysis and detailed design (DD).

3.1 Shape creation

For instance, simple search for a 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. The architecture profession is not known for being quick to change but as the design process goes digital and clients demand more value from their projects, graphical programming in this case could notably automate conceptual design process. Once creating the program for a building or a structure a designer can “play” with its initial parameters in order to obtain optimal ones.

In the Figure 3.2 an interface of a graphical program, or a script, for a building (b) and a building form described by the program (a) are presented. Script is a set of interconnected commands that consistently create elements of a building, assign types of elements, materials, properties, etc. Due to small scale of a picture, the script below is presented only for a general understanding of its structure and can be fully studied only with use of the software by which it was created.

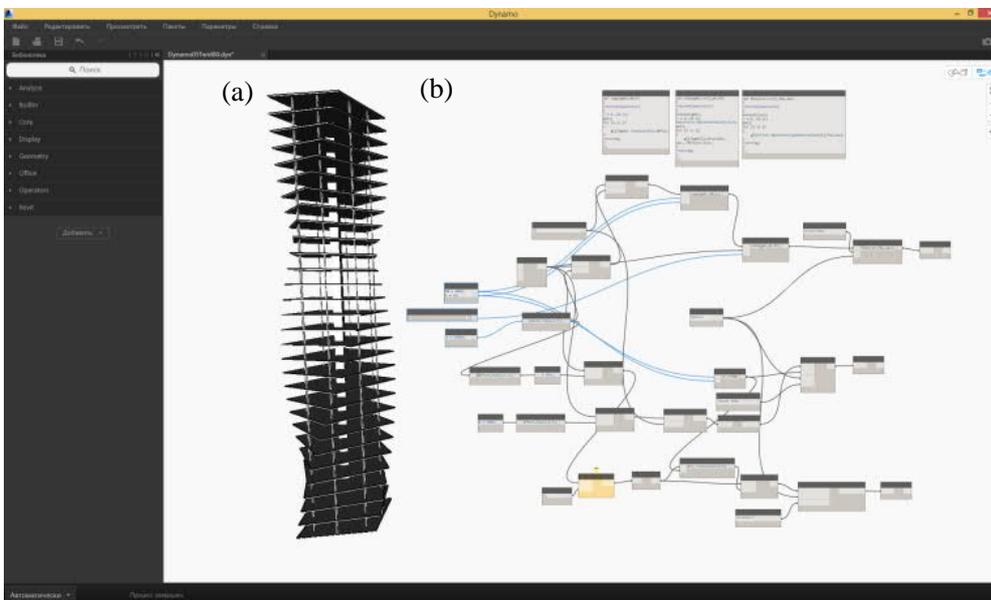


Figure 3.2: (a) Result of a graphical program (tall building structure). (b) Interface of the graphical program

In Figures 3.3 and 3.4 sets #1 and #2 of different initial parameters of the building (as the initial parameters here are taken such parameters as number of floors and their high, floor slab length and rotating angle of the building) and its resulted shapes are shown.

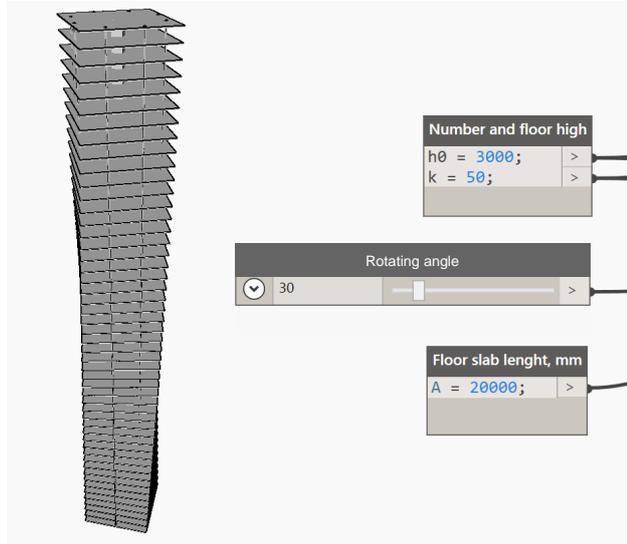


Figure 3.3: Set #1 of initial parameters and corresponding results of a graphical program

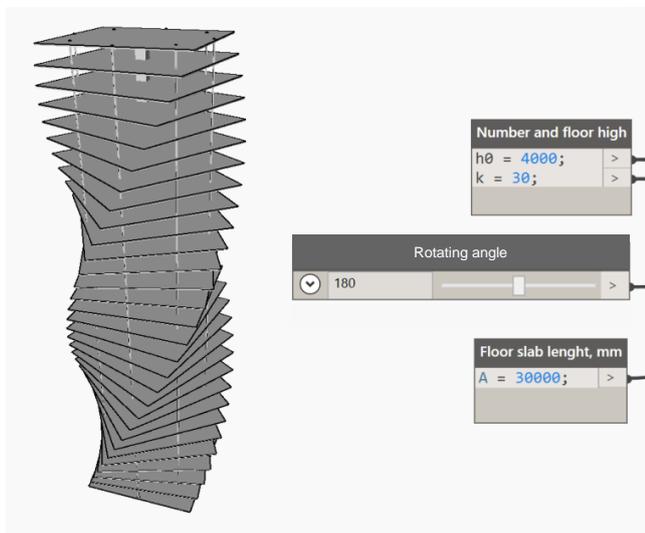


Figure 3.4: Set #2 of initial parameters and corresponding results of a graphical program

Graphical programming is a new approach in AEC design and it brings completely new possibilities for designers and customers and allows significantly automate early design stage. We propose to expand this approach with build-in databases of optimal and well-

tested design solutions. In this case software will also assist users by giving them technical prompts during design. For instance, it will automatically suggest an optimal cross-section of a structure depending on its structural parameters, material, boundary conditions etc. Thus, in case of, for example, floor slab design a program suggests a range of different floor slab structures (concrete, steel, standing on columns or suspended, etc.). However, standard functionality of existing software may also be used for building a BIM model.

3.2 Function Analysis of a BIM

3.2.1 Interaction matrix

Building an interaction matrix is the first step of the Function Analysis process. Position of elements in space, their geometric characteristics and functions are not taken into account at this stage. The matrix of interactions represents the Building Information Model (BIM model) as a system of interacting individual elements in order to perform the functions assigned to them. Identifying presence of interaction between the elements of the system is the key goal at this stage of analysis. The final aim of such step is to automatically create the interaction matrix based on results of the BIM model interaction analysis. In order to do this, the following actions must be performed:

1. Analyse the BIM model for presence of physical interaction between its components;
2. Output the result as the final interaction matrix in a user-friendly way.

Algorithm for interactions identification of the BIM model's elements:

As a demonstrative example, the following simplified system, shown in the Figure. 3.5, consisting of three elements has been considered. The system can also be represented as a sequential list of elements.

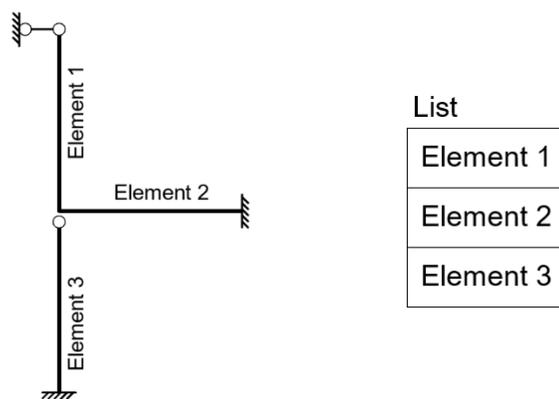


Figure 3.5: The studied simplified system and the list of its elements

Further, each element of the list has sequentially been examined with respect to the whole list of elements (see Figure 3.6). The elements may either interact (i), do not interact (ii) or self-interact (iii).

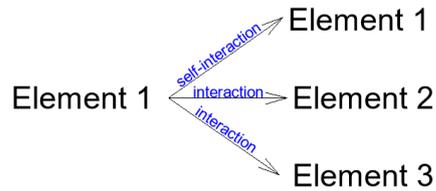


Figure 3.6: Interactions of the Element 1

After that self-interactions of elements have been excluded (see Figure 3.7).

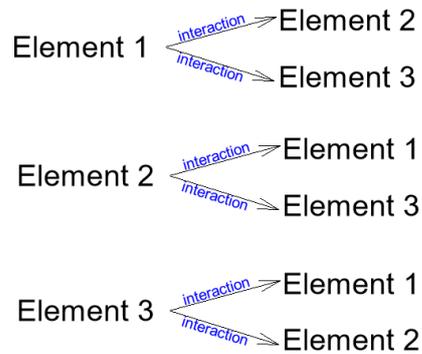


Figure 3.7: Interactions of elements, excluding self-interactions

Based on the data obtained from such analysis, a matrix of interactions has been created (see Figure 3.8).

	Element 1	Element 2	Element 3
Element 1		✓	✓
Element 2	✓		✓
Element 3	✓	✓	

Figure 3.8: Matrix of interaction

Output of the analysis result:

For automation of the process a graphical program (script) has been created (see appendix A) in the Dynamo environment. After the script has been run, a table is automatically created in an Excel file, which is generated based on the analysis of the BIM model's elements interactions. Output of results in the text form is the clearest and most understandable way. The resulting matrix can be quickly updated by re-running the script if the BIM model has been changed. The data from the interaction matrix can be used for further analysis, if necessary.

3.2.2 Determination functions of elements

The second step in the function analysis process of the BIM model is creation of a matrix of functions of its elements. At the previous step, while creating the interaction matrix, the geometric characteristics of the elements and their position in space were not taken into account. The goal of the interaction matrix is to reveal the fact of physical interaction among the elements. The next step in the analysis is definition of functions of the interacting elements in relation to each other. Thus, we gradually go deeper into the analysis of the model, moving from general to particular.

Algorithm of actions for identification of functions of elements:

Based on the data obtained during the interaction matrix creation, the number of interactions in the model can be evaluated. In order to do this, the intersection matrix can be presented in the form of the following table 3.1:

Table 3.1: Tabular representation of the interaction matrix

Element 1	↔	Element 2
Element 1	↔	Element 3
Element 2	↔	Element 1
Element 2	↔	Element 3
Element 3	↔	Element 1
Element 3	↔	Element 2

Let us return to our simplified model (see Figure 3.5) and consider the functions of the elements. Let us assume that the live load in our system acts along the Z axis and no other loads are applied to the model. Figure 3.9 shows that the Element 1 compresses the Element 3, and the Element 2 bends the Element 1 and compresses the Element 3.

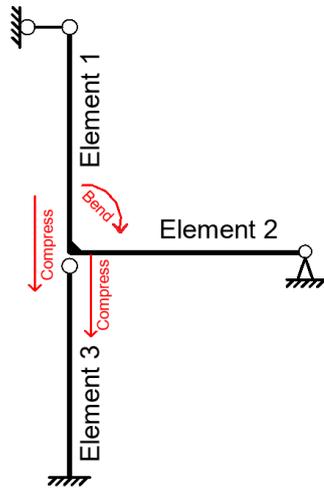


Figure 3.9: Graphical representation of functions in the simplified model

Thus, the interaction Table 3.1 can be converted into a function table 3.2.

Table 3.2: The table of functions

Element 1	-	Element 2
Element 1	Compress	Element 3
Element 2	Bend	Element 1
Element 2	Compress	Element 3
Element 3	Holds	Element 1
Element 3	Holds	Element 2

Further, for clarity and similarity of the two previous steps results, we represent the function table in the form of a matrix of functions (see Figure 3.10). The elements are located vertically and horizontally and their functions are at the intersection. The following legend is used for the functions:

1. Compress – C;
2. Bend – B;
3. Stretch – S;
4. Torque – T;
5. Hold (Support) - H.

	Element 1	Element 2	Element 3
Element 1	-	-	C
Element 2	B	-	C
Element 3	H	H	-

Figure 3.10: Matrix of functions

Defining functions by categories of elements:

The purpose of the elements` functions definition is the data preparation for ranking the BIM model`s elements. Therefore, in this investigation it was decided to take into account the functions of elements that require special attention: compression, bending, torsion.

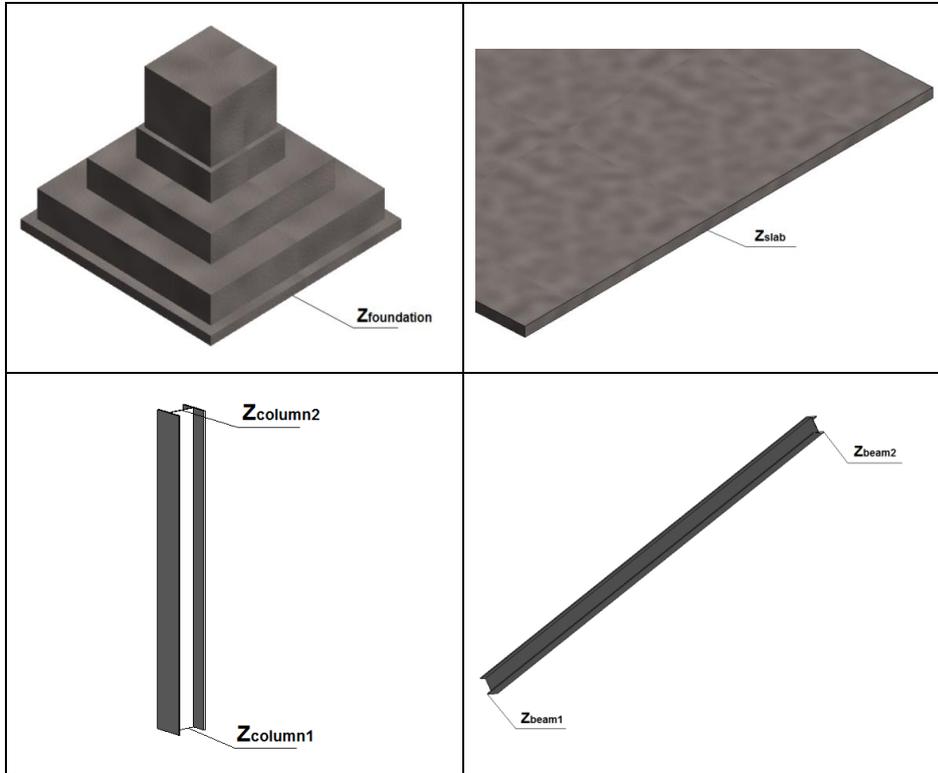
The Table 3.3 below shows the functions that correspond to interactions of the elements from different categories. The categories were chosen as the most commonly used in framed building systems.

Table 3.3: Defining functions by categories of elements

Category 1	Category 2	Hinged connected	Function
Foundation	Column	+	C
Foundation	Column	-	C + B
Column	Column	+	C
Column	Column	-	C + B
Column	Beam	+	C
Column	Beam	-	C + B
Beam	Slab	+	C
Beam	Slab	-	C + B
Beam	Beam	+	B
Beam	Beam	-	B + T

In order to determine functions of the elements programmatically, it is also required to specify the position of elements in space, namely the key coordinates of the elements in the BIM model. It is important to specify the coordinates of the bottom and the top for the linear objects such as beams and columns, and the lower level for the three-dimensional elements such as foundations. A floor slab is also considered as a three-dimensional element, thus, the lower level at each point of the slab is equal. This idea is presented graphically in the Table 3.4 below.

Table 3.4: Location of Z coordinates of different categories of elements

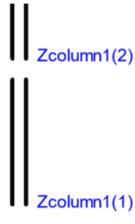
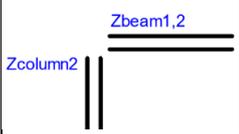
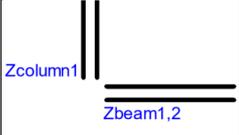
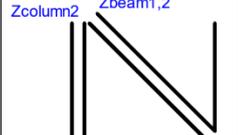
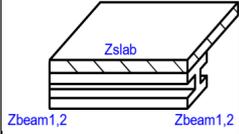
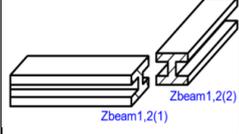


The functions of interest exist when the following conditions are met (see Table 3.5):

Table 3.5: Direction of interaction

Category 1	Category 2	Condition	Scheme of interaction	Description
Foundation	Column	$Z_{foundation} < Z_{column1}$		1) Column influences on foundation, hence, the column has a function. 2) Foundation holds Column

Table 3.5: Direction of interaction (continue)

Category 1	Category 2	Condition	Scheme of interaction	Description
Column (1)	Column (2)	$Z_{column1(1)} < Z_{column1(2)}$		1) Column (2) influences on Column (1), hence, the column (2) has function. 2) Column (1) holds Column (2)
Column	Beam	1) If $Z_{beam1} = Z_{beam2}$:		1) Beam influences on column, hence, the beam has function. 2) Column holds beam
		1.1) $Z_{column2} = Z_{beam1,2}$		
		1.2) $Z_{column1} = Z_{beam1(2)}$ (only for rigid connection)		
		2) If $Z_{beam1} \neq Z_{beam2}$:		
		2.1) $Z_{column2} = Z_{beam1(2)}$		
Beam	Slab	$Z_{beam1}(Z_{beam2}) < Z_{slab}$		1) Slab influences on beam, hence, the slab has function. 2) Beam Holds slab
Beam (1)	Beam (2)	$Z_{beam1,2(1,2)} = Z_{beam1,2(1,2)}$ and $X_{beam1(1)} < X_{beam2(1)} < X_{beam1(2)}$		Beam (2) influences on beam (1), hence, the beam (2) has function.

Output of the analysis result:

It is supposed to perform the information output by analogy with the matrix of interactions. For automation of the process a graphical program (script) has also been created (see appendix B) in the Dynamo environment. After the script has been run, a table is automatically created in an Excel file, which is generated based on the analysis of the BIM model's elements functions.

3.2.3 Function diagram

Creation of a function diagram is the third step in the function analysis process according to the suggested model.

The function diagram displays the 3D model in a 2-dimensional form, in which each element is presented in the form of a block with the element's name. It is called the "block of the element". The interaction between the blocks is displayed in the form of an arrow. Hereinafter - "arrow of interaction". Presence of the arrow between the blocks indicates presence of interaction between the elements and direction of the arrow indicates direction of an action. Nature of interaction (functions), as a rule, is written above the arrows. Creation of the function diagram is especially important for the analysis of complex systems with a large number of elements and functions, since, the function diagram is a convenient tool for monitoring the unwanted functions and state of the model after trimming when the function analysis may be repeated from the first step.

The function diagram for the model, which was considered earlier, is shown in the Figure 3.11.

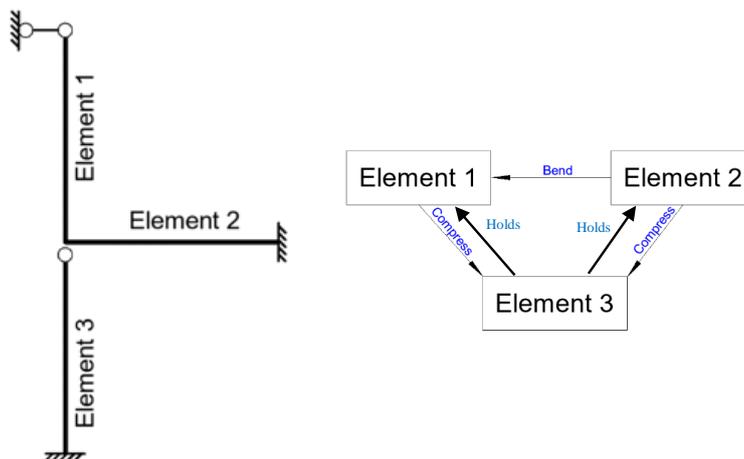


Figure 3.11: Function diagram of the studied system

The elements of the considered model are all located in the same plane, so creation of the function diagram does not cause difficulties, however, when it comes to models which elements are located in all three dimensions OX, OY and OZ, it becomes necessary to adopt new rules, due to the need of transformation the three-dimensional space into a two-dimensional one.

Function diagram creation. Common principles:

In order to generalize the method, a two-dimensional model has been developed into a three-dimensional one. For that purpose, several elements were added along the plane OY (see Figure 3.12). When it comes to placing the elements in the form of blocks in the function diagram all the elements of the model have to be grouped according to some common principle. For forming this principle, the Z coordinate of the lowest point of each element was chosen.

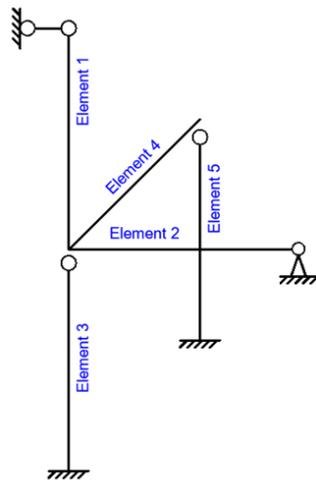


Figure 3.12: a three-dimensional studied model

For the following categories of elements, most commonly used in the framed building systems, the following levels are used during the analysis:

Column- Z_{column1} ;

Foundation - $Z_{\text{foundation}}$;

Floor slab - Z_{slab} ;

Beam - Z_{beam1} or Z_{beam2} (a lower value to be selected)

- Let us assume that the length of each element of the model shown in the Figure. 3.12 is equal to 1m. The coordinates of the lower points of the elements are also shown in the Figure 3.13.

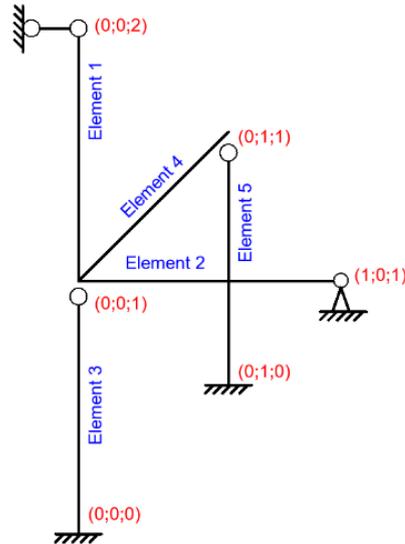


Figure 3.13: a three-dimensional studied model with coordinates

- Let us create a Table 3.6 on basis of the data from the model above, in the first column of which the names of the elements are indicated and in the second one the coordinate Z of the lower level of the elements;
- Let us group the contents of the table into levels equal to the Z coordinate, as shown in the Table 3.6.

Table 3.6: Grouping by the coordinate Z

Level in FD	Element's name	Z coordinate (m)
Level 1	Element 3	0
	Element 5	
Level 2	Element 1	1
	Element 2	
	Element 4	

- Let us locate the blocks of the elements in space of the function diagram according to the detected levels. Elements are placed with an equal step symmetrically to the central axis (see Figure. 3.14).

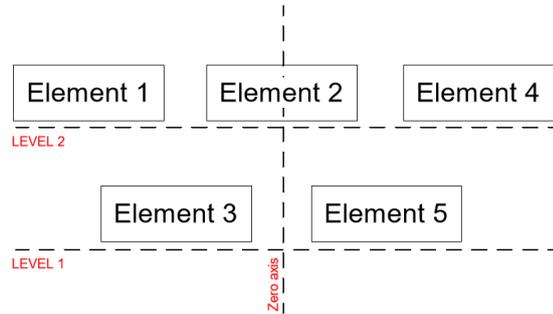


Figure 3.14: Blocks of elements placement

Software implementation:

Implementation of this step by the software is carried via analysis of the BIM model's elements as follows:

- 1) The graphical program (script see in appendix C) extracts the coordinates of the bottom level of each individual element;
- 2) Based on the extracted data, the list of elements is divided into several sub-lists, all elements of the same list have a common Z coordinate. Each sub-list corresponds to a separate level in the function diagram;
- 3) Next, families of blocks are created that are located on the drawing view in Revit © with an equal step along X in an amount equal to the number of elements in each separate sub-list and with an equal step along Y in an amount equal to the number of sub-lists;
- 4) The element name is written to the block's parameters.

The procedure for creating arrows of interaction:

In order to create the arrows of interaction in the function diagram, let us consider the matrix of functions for the studied model. The matrix consists of influencing elements located vertically and exposed to influence ones located horizontally respectively. At the intersection of horizontal and vertical axes there are functions of the acting element. That is why, it is necessary to read the matrix of functions from left to right, as indicated in the Figure 3.15 (left). Element 1 compresses Element 3. Thus, the arrow of interaction for the Element 1 - Element 3 will look as shown in the Figure 3.15 (right).

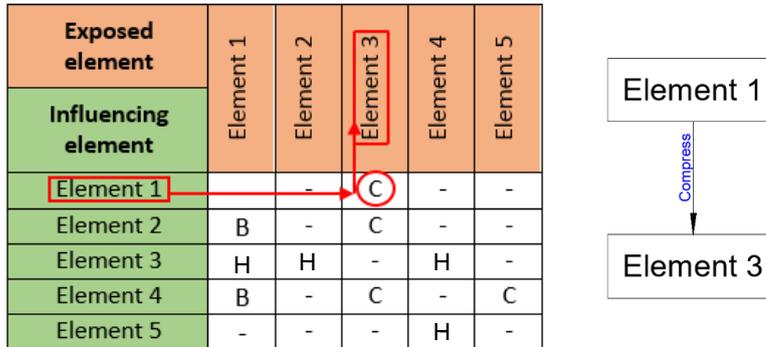


Figure 3.15: Defining direction of an arrow and its graphical representation

Function diagram generation. Software implementation:

Implementation of this step by the software is also carried via analysis of the BIM model's elements as follows:

1. The graphical program (script see in appendix C) extracts the coordinates of the bottom level of each individual element;
2. Based on the extracted data, the list of elements is divided into several sub-lists, all elements of the same list have a common Z coordinate. Each sub-list corresponds to a separate level in the function diagram;
3. Next, families of blocks are created that are located on the drawing view in Revit © with an equal step along X in an amount equal to the number of elements in each separate sub-list and with an equal step along Y in an amount equal to the number of sub-lists;
4. The element name is written to the block's parameters.

Thus, the function diagram for the studied model looks like in the Figure 3.16.

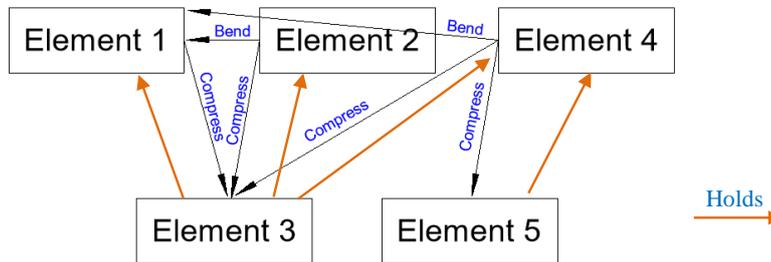


Figure 3.16: Final function diagram of the studied system

In order to create arrows of interaction automatically by the software, a matrix of functions is used. The program performs the following algorithm of actions:

1. The matrix of function of the BIM model is analysed and, as a result, a list with the “Element - Function - Element” elements is being created;
2. Within the function diagram the elements are being searched by their name, according to the list created;
3. A family is being created based on the arrow line in Revit. A parameter is being added to the family to which the function will be written later;
4. An interaction arrow is being created from the influencing element to the exposed one. The arrow is being created as a line in two clicks from one object to another. In order to find the point of the first and second clicks, the coordinates of blocks of the influencing and exposed elements in the list are being tracked;
5. The function of the influencing element is being written above the arrow.

3.3 Ranking

Ranking is a procedure that precedes the main objective of the function analysis - trimming. It implies a discrete examination of the elements of the BIM model for a number of criteria, according to which the elements are assigned a rank. The higher the rank of the element, the higher its significance in the BIM model, and the higher its chance of remaining in the model after trimming.

According to different ranking methods, criteria for the model evaluation have different representation: alphabetic, numerical and so on. The numbers obtained as a result of ranking are summed up for an element, the letters are added to the number and also have significance.

3.3.1 The first ranking rule

Closeness to a target function

Performance of the elements in the framed system is, as a rule, reduced to one final goal. For example, the work of the beams is reduced to supporting the floor slab. In turn, those beams are supported by columns. From the above, it can be concluded that the work of beams and columns of the first floor is reduced to providing a stable position in the space of the first floor slab. Floor slab is required in order to carry the live load, which includes weight of people, equipment, etc. Thus, it can be concluded that the slab is the key element for achieving the ultimate goal of design and operation.

All the elements have been combined into three main groups according to the degree of closeness to a target function:

1. Category "A" - high importance of elements;
2. Category "B" - the average significance of elements;
3. Category "C" - low significance of elements.

The following elements have been identified in the framed systems, the functions of which are targeted, since such elements cannot be trimmed:

1. Foundations;
2. Floor slabs;
3. Roof slab.

The listed elements belong to the first group and are marked with the letter "A".

Elements of the second group are the elements which performance is aimed at helping to achieve the target function. Those elements are marked with the letter "B". Such elements also have high level of significance in the BIM model and they can be identified through the following criteria:

1. The element interacts with the element that performs the target function;
2. The Z coordinate of the element's bottom point is lower than the lowest point's coordinate of the element performing the target function

Elements that do not interact with the "target elements" or have the Z coordinate higher than the Z coordinate of the target element, refer to the third group and are marked with the letter "C".

3.3.2 The second ranking rule

Harmful functions

An important factor in the work of a structure is the functions of its individual elements. Along with target functions, there are so-called harmful functions caused by certain factors. For example, the rigid connection of two columns provokes appearance of both compression and bending forces, and the hinged one – only compression. The bending force is considered here as more harmful, since the structure requires more materials in order to resist such stress condition. Ideally the structure could carry the load without causing any internal stresses in the structural elements. Anyway harmful functions will exist in the system but our suggested method gives tools for early identification of

harmful functions and ranking of corresponding elements for further analysis and actions. Presence of specific harmful functions decreases the element's rank. The following types of functions are considered as harmful and assigned a certain number of points:

1. Stretch – (-1);
2. Compress - (-2);
3. Bend - (-3);
4. Torque - (-4).

The points are assigned according nature of structural mechanics. The bigger internal stresses causes specific stress-strain state, the more negative points it receives.

3.3.3 The third ranking rule

Useful functions

The third rule is the opposite to the second one and takes into account only presence of the positive function, which is:

1. Hold – (+1).

Let us consider the system shown in the Figure 3.17, let us assume that the Element 2 performs the target function – carries vertical load. The other elements carry only self-weight. The system has been analysed according to the rules presented above.

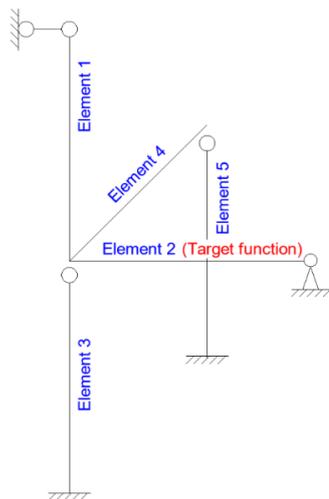


Figure 3.17: The system for ranging of elements

1. According to the 1st ranking principle, the Element 3 receives “B”, since the Element 2 performs the target function and the Element 3 holds the Element 2, the Element 2 receives “A”;
2. According to the 2nd ranking principle, the Element 2 bends the Element 1 and compresses the Element 3, the Element 4 bends the Element 1 and compresses the Element 3, that is why the Elements 2 and 4 receive (-3-2=-5), the Element 1 compresses Element 3 and receives (-2);
3. According to the 3rd ranking principle, the Element 3 and the Element 5 have positive functions. The Element 5 holds the Element 4 and receives +1. The Element 3 holds the Elements 1, 4, 2 and receives +1+1+1=+3. The results of the total ranking are given in the Table 3.7.

Table 3.7: Results of ranking

Element's name	Closeness to the target function	Presence of negative functions	Presence of positive functions	Ranking factor	Rank
Element 1	C	-2		-2C	4
Element 2	A	-5		-5A	1
Element 3	B		+3	B+3	2
Element 4	C	-5		-5C	5
Element 5	C		+1	C+1	3

The overall ranking factor of the elements is the total sum of negative and positive points based on results of the elements evaluation for all three principles. The overall ranking factor of the element is represented as follows:

$$R = (-X)N(+Y) \quad (1)$$

Where, X is the sum of harmful functions of an element;

N - the letter of the element's category;

Y - the sum of positive functions of an element.

3.4 Trimming

Trimming is the main objective of the functional analysis. At this stage all non-functional elements are “cut off” and the useful functions of the elements are transferred to other elements of the model.

Rules of trimming:

1. Removal of elements happens only if they fall into the category “C”;
2. Elements with harmful functions are highlighted in the model as elements “requiring further attention”.

After trimming the system has been transformed into the following one, shown in the Figure 3.18:

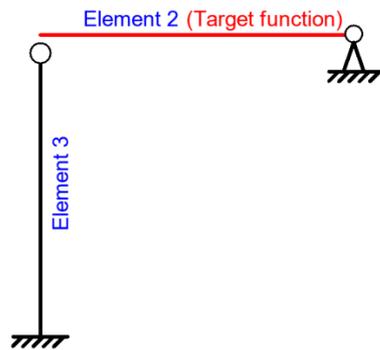


Figure 3.18: The studied system after trimming

Table 3.8: Trimming report

Trimmed elements	Elements requiring attention
Element 1	Element 2
Element 4	Element 3
Element 5	

After trimming the conceptual designer can move forward and try to reduce the index of harmful functions for the elements requiring attention. Now it can be done easily and systematically. For instance, for the Element 2 that is bent by the live load we can change its stress-strain state to compression or even tension by changing its radius of curvature. Similar can be done for the Element 3. Instead of using the standing column, we can apply a tensioned suspended column. After function analysis, ranking and trimming are done, such solutions become obvious and systematic. In general, the final structure performs equal functionality but is less material-consuming and more optimal and prepared for further structural analysis and detailed design. These further stages will now require less time and iterations.

3.5 Contradiction analysis

Contradiction analysis is the final part of the conceptual design process according to the developed methodology. As specified in the block diagram (see Figure 3.1), this process starts with an already optimized BIM model and acts as an assistant in making competent inventive engineering decisions. After completion of 2 stages: shape creation and function analysis, the contradiction analysis is the conclusive revision of the system.

The contradiction analysis includes 40 inventive techniques for technical contradictions elimination. A technical contradiction in TRIZ is a situation where an attempt to improve one characteristic of a technical system causes worsening of its other features. For more effective organization of this technique application, a special table has been developed by the TRIZ creator Genrich Altshuller (Altshuller et al. 1997). The table is called the Contradiction Matrix and there are the vertical columns that are the characteristics of technical systems needed to be improved and the horizontal rows that are the inadmissibly worsening characteristics. At the intersection of the corresponding columns and rows there are the numbers of engineering solutions application of which may guide the designer to elimination of the arisen technical contradiction.

In order to purposefully use those principles, the designer ought to have some practical experience, however, if the experience is still limited that a sequential application of the various inventive principles for solving the contradictions can also lead to a positive result.

The contradiction analysis is the quite universal method and applicable to many different fields. However, for working in a specific narrow direction the content of the contradiction matrix is better to be revised. Since not all the inventive principles may find their wide application in construction and, additionally, for adapting the common language for building designers who may not even be familiar with TRIZ, the specially adapted Construction Contradiction Matrix (CCM) has been developed based on the classic one.

For development of the model, revision of all the classic engineering parameters has been performed in order to identify the most suitable ones for use in the construction area. The list includes the following characteristics of the structural systems:

1. Weight of structure/element of structure;
2. Length of structure/element of structure;
3. Area of structure/cross-section;
4. Volume of structure/element of structure;
5. Structural Shape;

6. Stability of the structures' composition;
7. Internal/External Strength;
8. Duration of action/life time;
9. Illumination intensity;
10. Reliability;
11. Measurement accuracy;
12. Manufacturing precision;
13. Object-affected harmful factors;
14. Object-generated harmful factors;
15. Ease of manufacture;
16. Ease of operation;
17. Ease of repair;
18. Adaptability or versatility;
19. Complexity;
20. Difficulty of detecting and measuring.

Thus, the number of parameters has been reduced according to their possible application in design of buildings and formulation of the parameters has been adapted to the construction field. The matrix of contradictions for construction is shown in the Table 3.9. However, the final goal is to implement such a tool into the conceptual design process and automate it. In order to achieve this goal, it was decided to link the possibilities of this tool with categories of structural elements in the BIM model. That is why, for continue the analysis it becomes necessary to sort the identified characteristics of the structural elements according to their applicability to each category of the model's elements. In the presented analysis the following categories of the BIM model's elements have been considered: columns, beams, foundations and slabs. Sorting parameters by categories will reduce their number during selection from the list and minimize probability of an error due to possible choice of wrong parameters that are not applicable to particular category of structural elements.

Table 3.9: The Construction Contradiction Matrix

Worsening feature ↗	Improving feature ↘	Weight of structure/element of structure	Length of structure/element of structure	Area of structure/cross-section	Volume of structure/element of structure	Structural Shape	Stability of the structures' composition	Internal/External Strength	Duration of action/life time
		Weight of structure/element of structure	Length of structure/element of structure	Area of structure/cross-section	Volume of structure/element of structure	Structural Shape	Stability of the structures' composition	Internal/External Strength	Duration of action/life time
		10,1,29,35	35,28,40,29	30,2,14,18	35,10,19,14	15,10,26,3	26,39,1,40	40,26,27,1	6,27,19,16
		35,30,13,2	17,7,10,40	26,7,9,39	35,8,2,14	13,14,10,7	37	15,14,28,26	1,40,35
		5,35,14,2	35,8,2,14	-	-	-	39	9,40,28	-
		13,10,29,14	35,8,2,14	-	7,2,35	7,2,35	34,28,35,40	9,14,17,15	35,34,38
		26,39,1,40	39,37,35	2,38	34,28,35,40	33,1,18,4	22,1,18,4	10,30,35,40	-
		28,2,10,27	15,14,28,26	40	9,14,17,15	30,14,10,40	17,9,15	13,17,35	39,3,35,23
		2,27,19,6	1,10,35	2,10,19,30	35,34,38	-	39,3,35,23	-	-
		19,32,35	3,25	-	-	13,15,32	32,3,27,16	35,19	-
		10,28,8,3	15,29,28	32,35,40,4	2,35,16	10,40,16	-	11,3	34,27,6,40
		18,26,28	32,28,3	26,28,32,3	-	28,32,1	13	3,27,16	10,26,24
		10,1,35,17	2,32,10	2,29,18,36	35,10,25	32,30,40	18	3,27	-
		2,19,22,37	1,18	27,2,39,35	34,39,19,27	22,1,2,35	35,24,30,18	18,35,37,1	17,1,40,33
		35,22,1,39	-	22,1,40	30,18,35,4	35,1	35,40,27,39	15,35,22,2	22
		28,1,9	15,17,27	40,16	35	1,32,17,28	35,19	11,3,10,32	35,10
		6,13,1,32	2,25	16,4	-	32,15,26	32,35,30	32,40,25,2	1
		2,27,28,11	3	16	1	2,13,1	2,35,10,16	27,11,3	1
		19,15,29	1,35	15,16	-	1,15,29	35,30,34,2	15,3,32	2
		1,10,26,39	1,26	1,18,36	1,31	16,29,1,28	2,35,22,26	2,13,25,28	-
		25,28,17,15	26	2,35,30,18	2,17,26	15,13,39	35,22,39,23	27,3,15,40	25,34,6,35

6, 13, 28, 1	2, 26, 35, 39	19, 15, 29, 16	2, 27, 35, 11	6, 13, 1, 25	1, 27, 36, 13	35, 22, 1, 39	2, 22, 13, 24	28, 35, 27, 9	28, 35, 25, 26	3, 10, 8, 28	2, 35, 32
26	26	1, 35, 16	3, 18, 31	-	15, 17, 27	-	1, 18	2, 32, 10	32, 28, 3, 16	15, 29, 28, 11	-
2, 39, 30, 16	6, 36	15, 16	16, 25	18, 16, 15, 39	16, 40	22, 1, 40	27, 2, 39, 35	2, 29, 18, 36	26, 28, 32, 3	32, 35, 40, 4	-
2, 18, 26, 31	1, 16	-	1	4, 18, 39, 31	35	30, 18, 35, 4	34, 39, 19, 27	25, 10, 35	-	2, 35, 24	-
27, 13, 1, 39	29, 13, 28, 15	15, 37, 1, 8	1, 13, 2, 4	15, 34, 29, 28	1, 28, 13, 27	35, 1	22, 1, 3, 35	32, 30, 40	6, 28, 32	35, 1, 16, 11	32, 30
11, 22, 39, 30	2, 22, 17, 19	35, 30, 14	2, 35	32, 35, 30	11, 13, 1	35, 40, 27, 39	35, 24, 30, 18	30, 18	32, 35, 13	-	32, 3, 27
27, 3, 15, 28	2, 13, 28	35, 3, 32, 6	11, 1, 2, 9	32, 40, 3, 28	1, 3, 10, 32	15, 35, 22, 2	18, 35, 37, 1	3, 27	28, 6, 32	11, 28	35, 19
25, 34, 6, 35	-	2, 16	1	1, 16, 25	35, 16	21, 39, 16, 22	17, 1, 40, 33	-	10, 26, 24	34, 27, 6, 40	-
2, 24, 26	24, 17, 13	6, 22, 26, 1	15, 1, 13	13, 17, 1, 24	28, 24, 27, 1	19, 24, 39, 32,	1, 19, 32, 13	3, 32	6, 1, 32	11, 32, 13	*
27, 40, 28, 8	13, 35, 1	35, 13, 8, 24	11, 10, 1, 16	17, 27, 8, 40	-	24, 2, 40, 39	27, 24, 2, 40	11, 32, 1	5, 11, 1, 23	*	-
26, 24, 32, 28	2, 26, 10, 34	35, 5, 1, 10	10, 2, 13	25, 13, 2, 34	1, 35, 12, 18	3, 33, 26	28, 33, 23, 26	-	*	32, 3, 11, 23	11, 15, 32
-	26, 24, 32	-	25, 10	1, 32, 35, 23	-	4, 17, 34, 26	26, 28, 10, 18	*	-	11, 32, 1	3, 32
22, 19, 29, 28	22, 19, 29, 40	35, 11, 32, 31	35, 10, 2, 16	2, 25, 28, 39	24, 2	-	*	26, 28, 10, 36	28, 24, 22, 26	27, 35, 2, 40	15, 19
2, 21	19, 1	-	-	-	-	*	-	4, 17, 34, 26	3, 33, 39, 10	35, 2, 40, 26	35, 19, 32, 39
5, 28, 11, 29	27, 26, 1, 13	1, 13, 31	1, 35, 11, 10	2, 5, 10	*	-	24, 35, 2	-	6, 35, 25, 18	-	19, 35, 28, 26
2, 5	27, 9, 26, 24	15, 34, 1, 16	1, 12, 26, 15	*	2, 5, 13, 16	-	2, 25, 28, 39	1, 32, 35, 23	1, 13, 17, 34	27, 17, 40	28, 26, 19
12, 26	1, 13	1, 16, 7, 4	*	12, 26, 1, 32	35, 1, 11, 9	-	35, 10, 2	25, 10	1, 32, 13, 11	1, 11	15, 17, 13, 16
1, 15	29, 15, 28, 37	*	7, 1, 4, 16	15, 34, 1, 16	2, 13, 15	-	35, 11, 22, 34	-	13, 35, 2	13, 35, 8, 24	15, 1, 19
15, 10, 37, 28	*	15, 29, 37, 28	35, 1, 13, 11	32, 26, 12, 17	27, 26, 1	19, 1, 31	22, 19, 29, 40	26, 2, 18	27, 35, 10, 34	13, 35, 1	6, 32, 13
*	15, 10, 37, 28	1	-	-	6, 28, 11, 1	2, 21, 27, 1	22, 19, 29, 40	-	26, 24, 32, 28	27, 40, 28	32, 15

Automation of contradiction analysis

The software implementation of this tool should be implemented as follows:

1. Selection of the BIM model's element;
2. Selection of the worsening parameter;
3. Selection of the improving parameter;
4. Obtaining a number of the inventive solutions that may guide to elimination of the technical contradiction for the selected element.

Implementation of the 2nd and 3rd steps of the presented algorithm is performed using the "Windows Form" selection. Retrieving the information about the element, analysing the input data and output the analysis results is done with help of the Dynamo visual programming tool based on the Revit software. The script automating this process is presented in the appendix F.

The inventive solutions (principles) that may guide to elimination of the technical contradiction for the element of the BIM model are presented in appendix G. However, we would like to note that the developed matrix is not considered as an unique one since it is based on the classic contradiction matrix and uses all its principles. The idea for modification of the contradiction matrix is that application of familiar terms is more convenient than using general and not always understandable definitions.

3.6 Chapter conclusion

In this chapter the algorithm for automation of the conceptual design process of framed bearing structural systems has been created. This methodology includes three key steps: Shape Creation, Function Analysis and Contradiction Analysis.

The Shape Creation process includes two sub-steps: Shape selection and Selection of the BIM models' elements types. This tool enables designers to reduce time spent on creation of the relevant BIM model in Revit software.

The Function Analysis includes five sub-steps. First, the Interaction Matrix has been created for the of developed BIM model's structural elements. Secondly, the focus has been moved to the Function Matrix creation. This table shows character of the elements interaction. After that, the Function Diagram has been created based on the information retrieved from the Function Matrix and the Ranking Table has been obtained. In the Ranking Table the level of significance of the elements in the BIM model has been identified. Finally, based on the Trimming rules, the least functional elements have been excluded from the BIM model and the elements with harmful functions have been highlighted in the BIM model for further manual analysis. This tool helps to optimise

the BIM model on its early design stage without applying complex topology optimisation tools and allows receiving the most prepared system for the structural analysis avoiding large number of iterations.

The Contradiction Analysis, in turn, allows resolving technical contradiction in the structural system. Here the Construction Contradiction Matrix has been used. Along the axes of this matrix the worsening and improving parameters of elements are located. The suggested inventive principles for resolving the technical contradictions are located at the intersections of the axes. In order to resolve the technical contradiction for an element, it's enough to select its improving and worsening parameters in the BIM software and obtain the inventive principles to be used for further analysis.

4 Results

4.1 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 (Shaughnessy 1947).

4.1.1 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 on 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 analyse 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.

4.1.2 Survey results

As a result, 78 responses were received. 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% (see Figure 4.1).

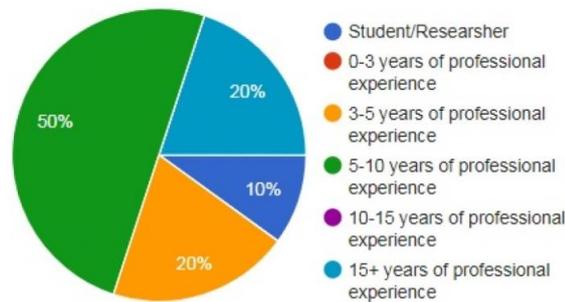


Figure 4.1: Experience in the field of building structures design among the respondents

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 (see Figure 4.2).

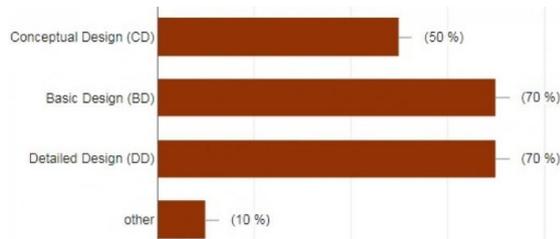


Figure 4.2: Distribution of areas of activities among the respondents

We assume that this is a fair 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 (Cavallucci 2009). Probably, this was due to the fact that the survey was also posted in the groups devoted to the subject of TRIZ.

50% of the replies stated that graphical programming tools were never used and not known for interviewed specialists. An important positive point is the result showing that 30% to some extent regularly use the advantages of graphical programming (see Figure 4.3). And more than 90% declared that they regularly face changes in the design or user requirements.

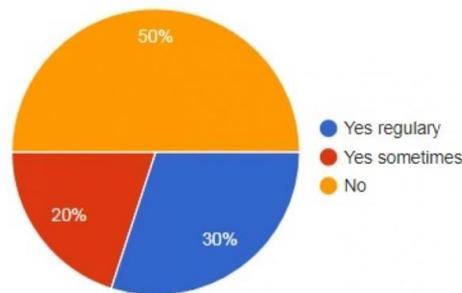


Figure 4.3: Regularity of using graphical programming tools among the respondents

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 the Figure 4.4, “is it useful if the software will automatically analyze your conceptually designed system for functionality of its elements and suggest optimization?” is in the Figure 4.5 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 the Figure 4.6.

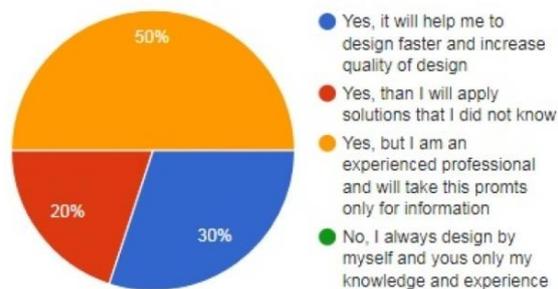


Figure 4.4: The respondents` attitude regarding such a proposed software feature as giving ready prompts from a database of proven solutions

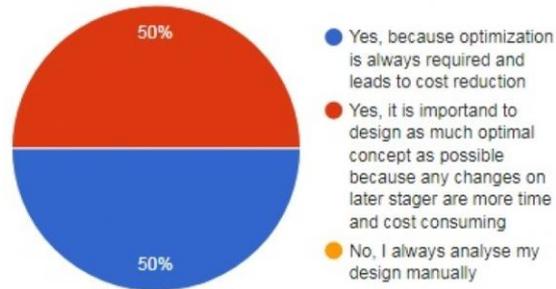


Figure 4.5: The respondents' attitude regarding such a proposed software feature as automatic analysis of a conceptually designed system for functionality of its elements and suggesting optimization

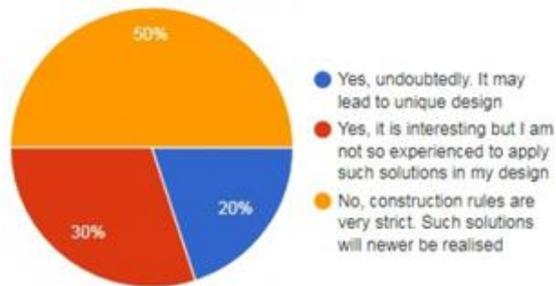


Figure 4.6: The respondents' attitude regarding such a proposed software feature as giving clues for finding non-trivial solutions that are not common in construction design

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 results are shown below. The respondents' attitude to demonstrated functionality of the proposed approach is shown in the Figure 4.7. Statistics regarding a question "can application of the demonstrated functions improve quality and speed of your work?" is shown in the Figure 4.8. Figure 4.9 reflects distribution of the proposed approach's functions that are found to be the most useful and applicable by the respondents.

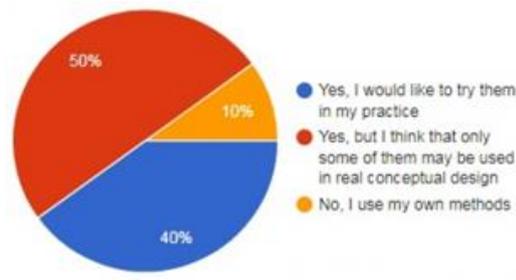


Figure 4.7: The respondents` attitude to demonstrated functionality of the proposed approach

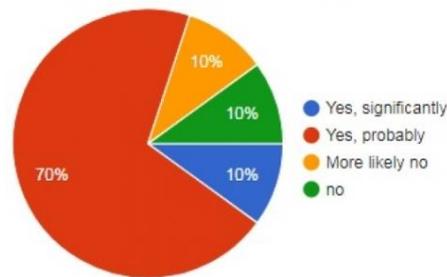


Figure 4.8: The respondents` attitude regarding probability of possible improvements that may be achieved applying functionality of the proposed approach

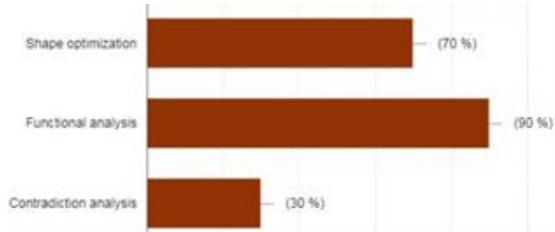


Figure 4.9: The proposed approach`s functions that are found to be the most useful and applicable by the respondents

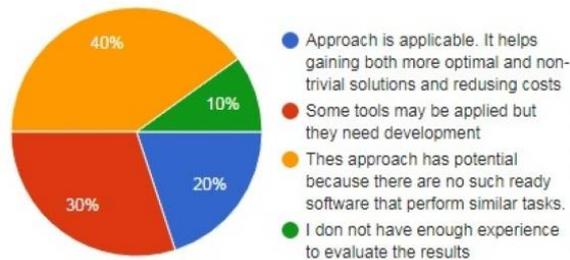


Figure 4.10 General evaluation of a novel approach for automated conceptual design of building structures

General evaluation of the novel approach for automated inventive conceptual design of building structures is provided in the Figure 4.10.

4.1.3 Survey results analysis

The survey results illustrate some of the positive and negative aspects. For instance, a significant part of the respondents is 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 function 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

4.2 Case study

In order to test the algorithm, we developed a program using visual programming tool Dynamo realized in Revit software environment. After a user creates a Building Information Model (BIM) of a framed building, this program performs the following algorithm of actions: construction of the interaction matrix, identification of functions of the model's elements, construction of the function model, ranking of elements and trimming. In this research we obtained a result that allows designers to automatically analyse and exclude non-functional elements from the model and further propose a solution to prevent unfavourable functions of its elements. The key advantage is that this analysis is being done on early design stage before deep structural analysis which is time and cost consuming. We provide a description the software prototype based on a frame building design case study.

4.2.1 Experimental model descriptions

In order to carry out the experiment a two-story framed structure (see Figure 4.11a) was constructed in Revit software. It includes 8 columns, 4 foundations, 1 slab and 12 beams. The choice of this composition of structures is justified by better visibility for representing the results. Despite the fact that the selected model does not include a large

number of elements it includes all the main categories of elements which are widely used in framed structural systems.

Geometrical characteristics (cross-section of beams and columns, thickness and spatial dimensions of the slab and foundations) are not taken into account and do not influence the results of the experiment. We consider functions which are performed by the elements. In order to present this idea as clearly as possible, it was decided to analyse the analytical model where each element is represented as a primitive (see Figure 4.11b).

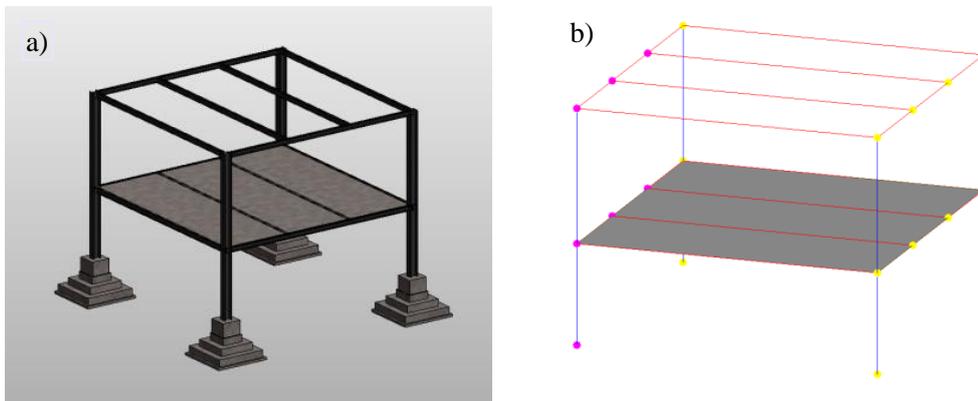


Figure 4.11: Experimental model. (a) Physical, (b) Analytical

The nodes of connection of individual elements are represented in simplified form. Yellow nodes are hinged connections and violet are rigid ones.

4.2.2 Interaction and function matrices construction

The script analyses the elements of the model and creates a matrix. The interaction matrix for the analysed model looks as shown in the Figure 4.12.

The script analyses the data received from the Interaction matrix and generates Matrix of functions according to the established rules. The matrix is shown in the Figure 4.13.

Legend used in the function matrix: C – compress; B – bend; B+T – bend and torque; B+C – bend and compress. In the Figure 4.13 the only harmful functions are evaluated since they have higher influence on the element's overall rank.

	1. Foundation	2. Foundation	3. Foundation	4. Foundation	5. Column	6. Column	7. Column	8. Column	9. Beam	10. Beam	11. Beam	12. Beam	13. Beam	14. Beam	15. Slab	16. Column	17. Column	18. Column	19. Column	20. Beam	21. Beam	22. Beam	23. Beam	24. Beam	25. Beam
1. Foundation				+																					
2. Foundation					+																				
3. Foundation						+																			
4. Foundation							+																		
5. Column	+							+	+						+	+									
6. Column		+							+	+					+	+									
7. Column			+							+	+				+	+									
8. Column				+				+			+				+	+				+					
9. Beam					+			+	+	+	+				+	+				+					
10. Beam					+	+		+	+	+	+				+	+									
11. Beam					+	+		+	+	+	+				+	+				+					
12. Beam						+	+	+	+	+	+				+	+									
13. Beam							+	+	+	+	+				+	+									
14. Beam								+	+	+	+				+	+									
15. Slab					+	+	+	+	+	+	+	+			+	+	+	+							
16. Column					+			+	+						+	+				+	+				
17. Column						+			+	+					+	+					+	+			
18. Column							+			+	+				+	+					+	+			
19. Column								+	+		+				+	+					+	+			
20. Beam																+				+	+				
21. Beam																+	+				+	+			
22. Beam																	+	+				+	+	+	
23. Beam																		+	+	+		+			
24. Beam																			+	+		+			
25. Beam																				+	+				

Figure 4.12: Interaction matrix of the experimental model

Influencing element	1. Foundation	2. Foundation	3. Foundation	4. Foundation	5. Columns	6. Columns	7. Columns	8. Columns	9. Beam	10. Beam	11. Beam	12. Beam	13. Beam	14. Beam	15. Slab	16. Columns	17. Columns	18. Columns	19. Columns	20. Beam	21. Beam	22. Beam	23. Beam	24. Beam	25. Beam
1. Foundation																									
2. Foundation																									
3. Foundation																									
4. Foundation																									
5. Columns	C																								
6. Columns		C																							
7. Columns			C																						
8. Columns				B+C																					
9. Beam					C			B+C	B	B	B	B													
10. Beam					C	C		B	B	B	B	B													
11. Beam						C	C	B	B	B	B	B													
12. Beam							C	B+C	B	B	B	B													
13. Beam									B+T	B	B	B													
14. Beam									B+T	B	B	B													
15. Slab								C	C	C	C	C	C												
16. Columns					C																				
17. Columns						C																			
18. Columns							C																		
19. Columns								B+C																	
20. Beam															C			B+C	B	B	B	B	B		
21. Beam															C	C		B	B	B	B	B	B		
22. Beam																C	C	B	B	B	B	B	B		
23. Beam																	C	B+C	B	B	B	B	B		
24. Beam																			B+T	B	B	B	B		
25. Beam																				B+T	B	B	B		

Figure 4.13: Function matrix of the experimental model (only harmful functions are shown)

4.2.3 Function diagram creations

According to the received data, Function Diagram (see Figure 4.14) is constructed on the drafting view in Revit. The blocks of element are created as Revit families. Arrows and notes are created using lines and text. The positive function ‘Hold’ is also shown in the figure, however, it may be hidden for better representation and identification of the harmful functions.

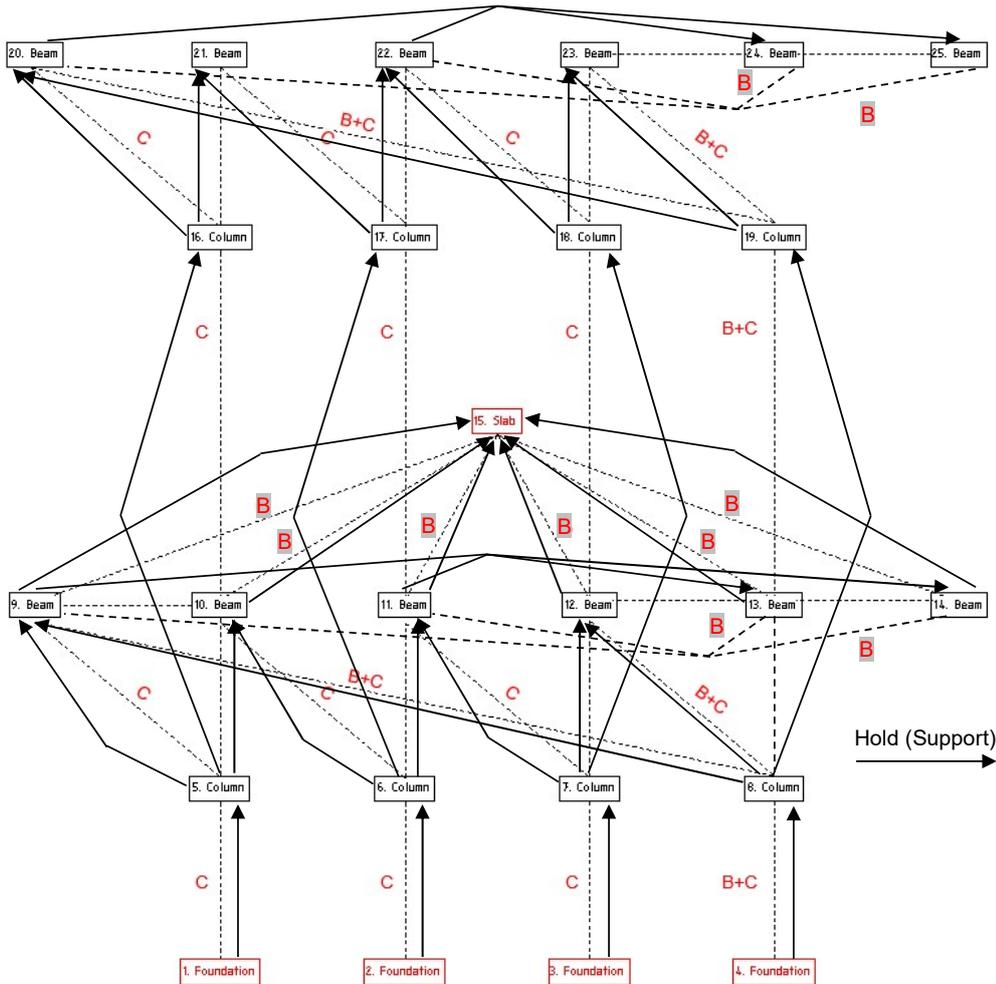


Figure 4.14: Function diagram of the experimental model

4.2.4 Ranking

According to ranking rules, the elements of the model are assigned a ranking factor and a rank. We have introduced the following rules: 1) Elements fall into 3 categories “A” -

high importance of elements; “B” - average significance of elements; “C” - low significance. 2) So-called harmful functions are assigned a certain number of negative points: Stretch – (-1); Compress - (-2); Bend - (-3); Torque - (-4). 3) So-called positive function is assigned a positive point: Hold (Support) – (+1).

Table 4.1: Ranking results

Element's name	Closeness to the target function	Presence of negative functions	Presence of positive functions	Ranking factor	Rank
1 Foundation	A		+1	A+1	1
2 Foundation	A		+1	A+1	1
3 Foundation	A		+1	A+1	1
4 Foundation	A		+1	A+1	1
5 Column	B	-2	+3	B+1	3
6 Column	B	-2	+3	B+1	3
7 Column	B	-2	+3	B+1	3
8 Column	B	-5	+3	-2B	5
9 Beam	B	-7	+3	-4B	6
10 Beam	B	-2	+1	-1B	4
11 Beam	B	-2	+3	B+1	3
12 Beam	B	-5	+1	-4B	6
13 Beam	B	-6	+1	-5B	7
14 Beam	B	-6	+1	-5B	7
15 Slab	A	-18	+1	-17A	2
16 Column	C	-2	+2	C	8
17 Column	C	-2	+2	C	8
18 Column	C	-2	+2	C	8
19 Column	C	-5	+2	-3C	10
20 Beam	C	-7	+2	-5C	11
21 Beam	C	-2		-2C	9
22 Beam	C	-2	+2	C	8
23 Beam	C	-5		-5C	11
24 Beam	C	-6		-6C	12
25 Beam	C	-6		-6C	12

4.2.5 Trimming

According to results of ranking the program identifies elements that are subjects for trimming and elements which design, geometric dimensions, material, the way of installation are needed to be considered in more detail.

Results of trimming:

1. Removal of elements occurs only if they fall into the category “C”;
2. Elements with harmful functions are highlighted in the model.

A list is formed and divided into two graphs as described above. Elements in the list are in order of decreasing rank from the less functional elements to more ones. Thus, the higher the element in the list, the higher probability for it to be excluded from the model or changing its function. The elements from the list are highlighted in the BIM model (see Figure 4.15). The yellow elements are the first candidates to be removed from the BIM model without losing its overall functionality. The red elements are subjects for possible modifications in order to reduce the number of negative points, or harmful functions. The not highlighted elements do not belong to the category ‘C’ and their number of positive functions is not less than the number of negative ones. Thus, the not highlighted elements do not require special actions and not subjects for further changes.

Table 4.2: Trimming report

Elements for trimming	Elements requiring attention
25. Beam (12)	13. Beam (7)
24. Beam (12)	14. Beam (7)
23. Beam (11)	9. Beam (6)
20. Beam (11)	12. Beam (6)
19. Column (10)	8. Column (5)
21. Beam (9)	
16. Column (8)	
17. Column (8)	
18. Column (8)	
22. Beam (8)	

4.2.6 Contradiction analysis

The analysis is carried out by selecting an element and choosing both improving and worsening parameters in the windows form. After that comes the result often consisting of several tips for resolving technical contradictions for the category which the element belongs to.

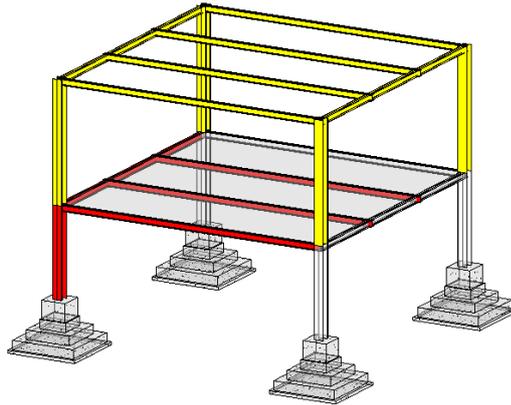


Figure 4.15: Highlighting elements after ranking

4.2.7 Case study conclusion

Presented case study shows that such TRIZ tools as function analysis and trimming can be applied to framed structural systems design. Modern design software allows engineers to perform such analysis directly in BIM environment. However, the need for some stages of function analysis realization in construction software can be discussed. For instance, the Interaction Matrix can be excluded from the function analysis since it is positioned as a sub-step to construction of the function matrix. Furthermore, the same algorithm of actions was repeated for both stages, so the stage of constructing the interaction matrix can be embedded into the algorithm of function matrix construction. The same can be said about construction of a function diagram. The function diagram is quite clear and easy to use for manual analysis of small structures, however, with software implementation on large projects the need for its construction can be discussed. The program accurately excludes the possibility of errors during analysis of the model and the interaction matrix and function diagram can be created and shown optionally.

With regard to further research, the development of ranking rules for wide range of structural schemes and assessment of additional groups of elements would make function analysis in construction field more accurate and reliable.

5 Summary of the publications

Results of studies were presented in the following events:

- 1) Second Russian-Finnish Doctoral Workshop on Marketing, Innovation and Entrepreneurship. GSOM, Saint-Petersburg State University, 1-2 June, 2015, Russia;
- 2) LUT Doctoral School Conference 10.12.2015, Lappeenranta University of Technology, Finland;
- 3) ETRIA World Conference TRIZ Future 2015: "Creating Value for Customers and Society" October 26-29, 2015, Berlin, Germany;
- 4) ETRIA World Conference TRIZ Future 2016 October 24-27, 2016, Wroclaw, Poland;
- 5) International Symposium on Design Science in Innovation and Engineering Research, 6.9.2017 - 7.9.2017, Lappeenranta University of Technology, Finland;
- 6) The 35th eCAADe Conference, 20th – 22nd September 2017, Rome, Italy;
- 7) ETRIA World Conference TRIZ Future 2017 "Bridging creativity in science, entrepreneurship, industry and education" October 4-6, 2017, Lappeenranta, Finland.
- 8) LUT Creativity Lab – PoliMi Workshop, 26-27 November 2018, Polytechnic University of Milan, Italy.

5.1 Interconnections between the publications

The dissertation consists of four interconnected publications that are devoted to the arisen research questions. The Publication I is the literature review on application of the Theory Inventive Problem Solving tools in the construction area and based on articles collected during the initial stages of the research process. Work on the article resulted to formation of the common research path. The Publication II is related to the general proposal for automation of the conceptual design process of framed bearing structural systems. Here the design algorithm and its key steps were described. The publication III is the development of technical realization for the proposed algorithm. Finally, the Publication IV is the evaluation of the proposed approach for automated conceptual design of building structures. In this paper results of the specially developed survey were summarized and analyzed. The publications are the result of an iterative research process in which each publication built on the findings from the previous work. The interconnections among the publications are shown in the Figure 5.1.

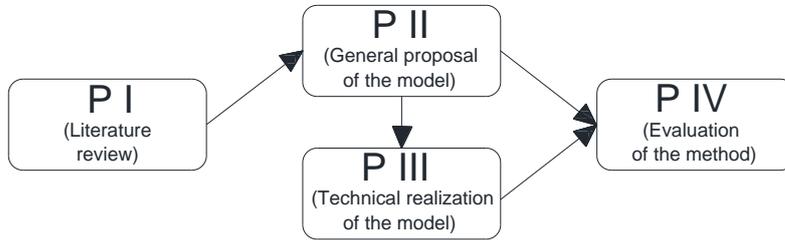


Figure 5.1: Interconnections between the publications

The Table 5.1 summarizes the key results of the publications and their main contributions to the overall thesis objective. Subsequent sections of this chapter present overview of each publication in more details.

Table 5.1: Summary of publications included in the thesis

Publication	I	II	III	IV
Objectives	Review the TRIZ tools used in construction field. Identify particular areas of application and determine gaps for further investigation	Develop the general proposal for automation of the conceptual design process of framed bearing structural systems.	Development the key principles for technical realization of the proposed algorithm	Evaluate the proposed approach for automated conceptual design of building structures.
Methodology	Literature review	Qualitative, Quantitative	Qualitative	Literature review, Quantitative
Related RQ(s)	RQ1	RQ2	RQ2	RQ2, RQ3
Main findings	The level of innovation in construction is still low and there is no common approach for the conceptual design process automation	The bearing structural systems can be systematically analyzed using tools for inventive product design	It was proven that the TRIZ tools can be integrated into existing construction design software	The proposed approach was evaluated as useful and helpful for conceptual design automation.
Contribution to the thesis	The main direction for the research was formed. The tools for supporting the automation of conceptual design in construction have been identified	The general logic for automation of the conceptual design process of framed bearing structural systems was developed and consistently described	Methods for the technical realization of the proposed algorithm have been developed and implemented	The relevance of the suggested novel approach was proven by both summarizing the literature review and analyzing results of the specially prepared survey.

5.2 Publication I: Application of TRIZ in Building Industry: Study of Current Situation

5.2.1 Study objective

In the modern professional world engineers and managers must have a universal intellectual set of tools that would enable them to find the right ideas in a well-structured methodological way avoiding consideration of knowingly false solutions leading to waste of time, missed deadlines, planned budgets, etc. Since the risk of failure in construction is higher than in many other industries (Kulatunga et al. 2006) it is not acceptable to use trial-and-error approach (especially for large-scale projects) in order to find ideas and solutions for the development and improvement of design procedures, structures and construction techniques. According to the ETRIA (the European TRIZ association) Worldwide survey performed in 2009, only 3,5% of construction professionals are devoted to the TRIZ, which means that TRIZ remains marginal in the building industry. This paper presents scientific indexed literature review to a) identify existing innovative approaches based on TRIZ tools which find their application in design and construction and help solving ongoing issues, b) justify relevance of further study of TRIZ application in building industry and, finally, develop a set of key objectives to be later investigated.

5.2.2 Main contribution

Despite the fact that innovation is not the key feature of construction industry, it cannot be considered to be a technologically lagging behind. The key players on the market are cautious about innovation possibly because reliability, stability and meeting existing codes requirements are more demanded aspects. However, real breakthroughs and proven ideas could destroy that conservatism barrier.

The literature review on the subject of TRIZ application in building industry has shown that a number of researchers are working in this direction and making attempts to use TRIZ tools when it is required to find unique ideas and solve specific complex issues in such areas as development of construction techniques and technologies, design of new structures and construction materials, construction project management and value engineering, etc. However, successful application of these tools is not possible without creative adaptation. On the other hand, the number of publications in this field is relatively small which allows us to conclude that TRIZ use is still very limited in construction.

The classic Theory of Inventive Problem Solving was created to solve common technical issues and, therefore, does not provide specific tools for specific industries. Despite that TRIZ has proven to be a quite unique methodology, there are still many controversial situations requiring TRIZ tools to be adapted to a specific industrial field, and construction is not an exception. The review result has shown that the TRIZ tools

are, however, used in construction and, hence, may be used the basis for development of a methodology for automated conceptual design of building structures.

5.3 Publication II: Computer-aided conceptual design of building systems. Linking design software and ideas generation techniques

5.3.1 Study objective

Early design stage in Architectural and Construction projects is a crucial part of sophisticated long-term design process, here many fundamental and critical solutions are taken into account. The smarter and less trivial solutions are developed during the CD, the more advanced, effective, and less costly design is gained. Those solutions can be found by using different techniques of ideas generation. In our digital century it is reasonable to link modern construction design software with ideas generation techniques in order to enhance and automate design creativity. Nowadays Building Information Modelling (BIM) became popular stream in construction design. Existing BIM software have range of instruments enabling designers to bring all their knowledge and experience into projects but, however, that software do not support users in searching for nontrivial conceptual ideas for design. That is why the ideas generation stage is still a separate, not automated and human-depended part of construction design. BIM and graphical programming for design are state-of-the art in modern construction design and Computer-Aided-Invention software is becoming more popular in different disciplines. Merging this with existing inventive techniques could add artificial intelligence into AEC design software and enhance and automate design creativity in conceptual design stage.

5.3.2 Main contribution

In this research there has been obtained a result that allows designers to automatically analyse and exclude non-functional elements from the BIM model and propose a solution to prevent un-favourable functions of its elements. The key advantage is that this analysis is being done on early design stage before deep structural analysis which is time and cost consuming. After the function analysis has been done, it is proposed to analyse the trimmed model using another TRIZ tool called Contradiction analysis. This part of analysis is the final part of the conceptual design phase according to the developed methodology. Contradiction analysis includes inventive techniques to eliminate technical contradictions. A technical contradiction in TRIZ is a situation where an attempt to improve one characteristic of a technical system causes worsening of another one. For more effective organization of use of techniques, a special table has been developed. There are the characteristics of technical systems need to be improved and characteristics that are worsened. At the intersection of the table graphs the numbers of solutions are indicated which help to eliminate the arisen technical contradiction. For

construction field the revision of all proposed technical characteristics was carried out in order to identify the methods most suitable for use in the construction area. The final goal is to implement those tools in the design process. For further research it is planned to validate the obtained results by giving the developed design scripts and user instructions to professional designers in order to independently test the algorithm and collect feedback. For that purpose, development of a questionnaire has been proposed.

5.4 Publication III: Early design stage automation in Architecture-Engineering-Construction (AEC) projects

5.4.1 Study objective

The key objective of this publication is development of the key principles for technical realization the earlier proposed algorithm and proving that the TRIZ tools can be integrated into existing construction design software.

5.4.2 Main contribution

Autodesk Revit® was selected as the basic and most promising software for realization of a proposal for conceptual design stage automation in AEC projects. In the approach software is supposed to self-analyse Building Information Model and suggest solutions in order to improve the system. For that purpose, it is suggested to use the TRIZ Function Modelling and rules of trimming. In order to teach software to extract a function model from BIM model a special script has been built. The script first automatically detects elements/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 interactions among elements of the system. On the next step the software defines functions of elements in the Interaction Matrix. For identification of interactions the script also applies special 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 on elements and functions. Also, the software helps to achieve a more complete and convenient work flow for design engineers as all is done within the BIM environment. Finally, having this overview is a prerequisite for performing 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 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 design engineer can accept other decline those proposals. In function ranking functions of elements are ranked on their level of usefulness. The higher 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. 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 analyse the BIM model and easily obtain nontrivial design avoiding complex processes of topology optimization and structural analysis which are issues for further detailed design. As a case study a simple beam structural system has been analysed.

5.5 Publication IV: Evaluation of a novel approach for automated inventive conceptual design of building structures

5.5.1 Study objective

This paper is the final part of the 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 analysed that may be integrated into modern design software in order to enhance the level of design automation and design creativity. 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 Modelling software using an open source graphical programming tools. 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.

5.5.2 Main contribution

In the article all the stated research questions were answered consistently. The current situation in the field of automation of the conceptual design process in the construction projects was studied by analysing the thematic publications. The relevance of the suggested novel approach was proven by both summarizing the literature review and analysing 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 useful and helpful. It was confirmed that such very potential instruments as graphical programming and TRIZ unfairly remain unnoticed by most specialists and the proposed method reveals all their possibilities. As for further development of the approach it was suggested to follow users' feedback and expand its functionality, convenience of use and adapt to cases from the real practice.

6 Discussion and conclusion

This research aims to developing an approach for automation of the conceptual design process of framed bearing structural systems. In order to achieve this goal, three research questions have been stated and answered consistently. Answers to those research questions and contribution of this research are elaborated in this section. Limitations of the research and future research directions are also discussed.

6.1 Answering the research questions

RQ1: To what extent the inventive problem solving techniques are used in the construction field?

This research question was answered in the Publication I by analysing the literature in the construction field. Thus, ongoing research and statistical data showed that construction lags behind many other industrial sectors such as IT, computers, software, automotive industry, electronics, mechanical engineering, etc., in terms of efficiency and productivity due to mostly lack of realizations of new ideas. At the same time modern construction companies are keen on innovations to be competitive on the market, which is why engineers and managers innovate when technology can be modified easily. On the other hand, construction industry is also known for its conservatism and professionals tend to use an accepted industry practice and norms in fulfilling client's need. Therefore, it seems quite logical to conclude that innovations must be on demand in the construction industry but, at the same time, the construction industry is considered slower in technology innovation in the past decades partially due to the characteristics of the industry. New solutions can be found by using different techniques of ideas generation, such as morphological charts, synectics, brainstorming, TRIZ tools, etc. TRIZ is believed to be one of the most effective and well-structured problem-solving techniques and it is well applicable to architecture and construction.

RQ2: To what extent is it relevant to develop a new approach for the conceptual design stage automation and what tools can be used for supporting automation of the conceptual design in construction?

Presented case study in the Publication II shows that such TRIZ tools as function analysis and trimming as well as the contradiction analysis can be applied in framed structural systems design. Modern design software allows engineers to perform such analysis directly in BIM environment. However, the need for some stages of function analysis realization in construction software can be discussed. For instance, the Interaction Matrix can be excluded from the function analysis since it is positioned as a sub-step to construction of the function matrix. Furthermore, the same algorithm of actions was repeated for both stages, so the stage of constructing the interaction matrix can be embedded into the algorithm of function matrix construction. The same can be said about construction of a function diagram. The function diagram is quite clear and

easy to use for manual analysis of small structures, however, with software implementation on large projects the need for its construction can be discussed.

In general, developers nowadays are 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.

RQ3: What features of the new method can ensure its wide application?

The set of principles for integration of TRIZ tools into construction design software was developed and realized in the Publications II and III. Autodesk Revit® was selected as the basic and most promising software for realization of a proposal. Moreover, this is the only software that has a built-in open source graphical programming tool for design which extends building information modelling with the data and logic environment of a graphical algorithm editor and enables users to significantly expand functionality of the software without having special knowledge of programming. All that means that nowadays there are all the possibilities to merge known tools for inventive problem solving and existing construction design software.

The relevance of the suggested novel approach was proven in the Publication IV by both summarizing the literature review and analysing 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 such TRIZ tools as Function analysis and Contradiction analysis 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.

6.2 Contribution of the research

In this research we have developed the novel approach for automation of the conceptual design process of framed bearing structural systems. The proposed technique allows designers to reduce design time of structures and, at the same time, enhance quality of its design. The logic of the method consists of several steps. First, at the initial step called “Shape Creation”, the design time is reduced significantly by using graphical programming which does not require serious programming skills and assessable for a wide range of designers. Since changes of user requirements are very probable in the beginning of design, some tools that help to follow those changes spending minimal amount of time are very required. Scripts created using graphical programming solve this issue well enough. When the structural shape is found and approved by project participants, the second step called “Function Analysis” helps to significantly reduce structural material and, hence, price of construction by automatic analysis of a BIM model and excluding non-functional elements from the model and proposing a solution to prevent unfavourable functions of its elements. After the function analysis has been done, the third step has been proposed for analysis of the trimmed BIM model using another TRIZ tool called “Contradiction analysis”. Using this tool helps designers to find inventive solutions and eliminate technical contradictions in the system which means that the structural system will not have worsening parameters. The key advantage of the approach is that all the analysis process is being done on early design stage before deep structural analysis which is time and cost consuming. All the described steps are automated and help designers to eliminate thinking and mental inertia and move them from “optimization” way of design to “invention” one which means that the structures may become more innovative and non-trivial rather than just optimal.

6.3 Limitations of the research

As any scientific work this research is limited by the focus taken. Since it focuses only on conceptual design process of framed bearing structural systems, it does not cover solid or combined structural systems as well as it does not go behind the early design stage. Also a variety of different loads and actions on bearing structures are not being considered for development of the main provisions of the method while they might also have some influence.

Moreover, implementation of the developed algorithm is limited by the selected software functionality. Additionally, evaluation of the approach is based on the survey, the results of which may slightly vary and depend on the pools of the respondents. However, all these limitations are conscious and do not misrepresent the main results achieved.

6.4 Future research directions

With regard to further research directions, development of ranking rules for wide range of structural schemes as well as assessment of additional groups of elements would make function analysis in construction field more comprehensive and reliable.

For the final closure of the problem related to the need of automation in the conceptual design process within building industry, it is necessary to introduce the results of this research into areal design process and evaluate the effect obtained.

Another possible research direction in this field is to evaluate potential of other TRIZ tools application in resolving the issue of conceptual design automation in construction projects.

References

- Abrishami, S. et al., 2014. Integration of BIM and generative design to exploit AEC conceptual design innovation. *Journal of Information Technology in Construction*, 19(August 2013), pp.350–359.
- Afzali, S.H., Darabi, A. & Niazkar, M., 2016. Steel frame optimal design using MHBMO algorithm. *International Journal of Steel Structures*.
- Altshuller, G.S., Shulyak, L. & Rodman, S., 1997. *40 Principles: TRIZ Keys to Technical Innovation* L. Shulyak, ed., Technical Innovation Center, INC.
- Coşkun K. and M. Cem Altun, 2011. Applicability of TRIZ to In-Situ Construction Techniques. In *International Proceedings of Economics Development & Research*. p. 17.
- Changsha, Associated Press in. “Chinese Construction Firm Erects 57-Storey Skyscraper in 19 Days.” *The Guardian*, Guardian News and Media, 30 Apr. 2015, www.theguardian.com/world/2015/apr/30/chinese-construction-firm-erects-57-storey-skyscraper-in-19-days. [Accessed October 22, 2018].
- Faber, Jaron, et al. “Best Building Design and BIM Software: Winter 2015 Rankings.” G2 Crowd, 28 June 2016, www.g2crowd.com/blog/best-building-design-bim-software. [Accessed October 22, 2018].
- Asad, S., Khalfan, M.M.A. & MacDermott, P., Promoting Innovative thinking within Construction. , pp.62–71.
- Bakker, H.M., Chechurin, L.S. & Wits, W.W., 2011. Integrating TRIZ function modeling in CAD software. In *Proceedings of TRIZfest-2011*.
- Becattini, Niccolò , Gaetano Gascini, and Francesco Rosa. “Embedding Biological Knowledge in a Conceptual Design.” *Computer-Aided Design and Applications*2016, 701–11.
- Becerik-Gerber, B. & Kensek, K., 2010. Building Information Modeling in Architecture, Engineering, and Construction: Emerging Research Directions and Trends. *Journal of Professional Issues in Engineering Education and Practice*.
- Bernal, M., Haymaker, J.R. & Eastman, C., 2015. On the role of computational support for designers in action. *Design Studies*.
- Blayse, A.M. & Manley, K., 2004. Key influences on construction innovation. *Construction Innovation: Information, Process, Management*, 4(3), pp.143–154.
- Brown, N.C. & Mueller, C.T., 2016. Design for structural and energy performance of long span buildings using geometric multi-objective optimization. *Energy and Buildings*.
- Cabrera, B.R. & Li, G.J., 2014. A lean-TRIZ approach for improving the performance of construction projects. In *Proceedings IGLC-22, June 2014 | Oslo, Norway*.
- Cavallucci, D., 2009. *World Wide status of TRIZ perceptions and uses a survey of results*, Available at: <http://etria.eu/portal/index.php/etria-projects-mainmenu-74/103>.
- Chang, P.-L., Yu, W.-D., Cheng, S.-T., Lee, S.-M., 2010. Exploring underlying patterns of emergent problem-solving in construction with triz. In *27th International Symposium on Automation and Robotics in Construction, ISARC 2010*. Bratislava,

- pp. 607–616.
- Chang, P.-L., Yu, W.-D.c, Lee, S.-M., 2012. A General Construction Problem-Solving Model based on lessons-learned approach. *Journal of the Chinese Institute of Civil and Hydraulic Engineering*, 24(4), pp.415–428.
- Chechurin, L., 2016. TRIZ in Science. Reviewing Indexed Publications. *Procedia CIRP*, 39, pp.156–165.
- Chechurin, L. & Borgianni, Y., 2016. Understanding TRIZ through the review of top cited publications. *Computers in Industry*, 82, pp.119–134.
- Chechurin, L.S. et al., 2011. Introducing trimming and function ranking to SolidWorks based on function analysis. *Proceedings of Triz Future Conference 2011*, pp.215–225.
- Chen, Z., Li, H., Chung, J.K.H., Shen, G.Q.P., Clements-Croome, D.J., 2006. A triz based value management process for selecting façade solutions. In *Inaugural Asia Pacific Value Convention 2006: The World of Innovation - Incorporating the 8th HKIVM International Conference and the 11th Biennial Conference of IVMA*. Hong Kong, pp. 288–295.
- Chiu, R. Sen & Cheng, S.T., 2012. The improvement of heat insulation for roof steel plates by triz application. *Journal of Marine Science and Technology*, 20(2), pp.122–131.
- Conall Ó Catháin, Darrell Mann., 2009. Construction innovation using TRIZ. In *Global Innovation in Construction Conference 2009*. pp. 296–306.
- Craig, S. et al., 2008. BioTRIZ Suggests Radiative Cooling of Buildings Can Be Done Passively by Changing the Structure of Roof Insulation to Let Longwave Infrared Pass. *Journal of Bionic Engineering*, 5(1), pp.55–66.
- Cui, H., 2014. Exploring Conflict Resolution Methods for Construction Projects: A TRIZ Theory Perspective. In *ICCREM 2014*. pp. 791–796.
- Dale, J., 2007. *Innovation in construction : ideas are the currency of the future*, Berkshire: The Chartered Institute of Buildinf.
- Ding, Z., Wang, J., Ng, F., 2012. Innovation and patent knowledge management in the construction industry. In *17th International Symposium on Advancement of Construction Management and Real Estate, CRIOCM 2012*. Shenzhen; China, pp. 833–842.
- Ding Z., Jiang S., Wu.J., 2013. Research on Construction Technology Innovation Platform Based on TRIZ. In *Proceedings of the Eighth International Conference on Intelligent Systems and Knowledge Engineering*, Shenzhen, China, Nov 2013 (ISKE 2013), pp. 211–223.
- Ding, Z. & Ma, J., 2014. An exploration study of construction innovation principles: Comparative analysis of construction scaffold and template patents. In *Proceedings of the 17th International Symposium on Advancement of Construction Management and Real Estate*. pp. 843–850.
- Efimov-Soini, N., Kozlova, M., et al., 2016. A multi-criteria decision-making tool with information redundancy treatment for design evaluation. *Proceedings of the NSAIS'16 Workshop on Adaptive and Intelligent Systems 2016*, pp.73–75.
- Efimov-Soini, N., Chechurin, L., et al., 2016. Method of Time-dependent TRIZ

- Function Ranking. In *TRIZ Future Conference 2016: Systematic innovation and creativity*.
- Efimov-Soini, N. & Chechurin, L., 2017. The Method of CAD Software and TRIZ Collaboration. In A. Kravets et al., eds. *Communications in Computer and Information Science*. Volgograd, Russia: Springer International Publishing, pp. 517–527.
- Efimov-Soini, N. & Uzhegov, N., 2017. The TRIZ-based Tool for the Electrical Machine Development. In *Progress In Electromagnetics Research Symposium*.
- Efimov-Soini, N.K. & Chechurin, L.S., 2016. Method of Ranking in the Function Model. *Procedia CIRP*, 39, pp.22–26.
- Fenton, M. et al., 2014. Automatic innovative truss design using grammatical evolution. *Automation in Construction*.
- Gazem, N. & Rahman, A.A., 2014. Interpretation of TRIZ Principles in a Service Related Context. *Asian Social Science*, 10(13), pp.108–130.
- Genrich Saulovich Altshuller and Rafael Borisovich Shapiro, 1956. About the Psychology of Technical Creativity (О психологии изобретательского творчества). *Questions of psychology (Вопросы психологии)*, 6, pp.37–49.
- Hsuan-Tzu Hsu, Tsai B.-S. and Chen K.-T., 2013. A TRIZ Approach to Business Management Formulation - A Case of HRMS Industry. In *Proceedings of the International MultiConference of Engineers and Computer Scientists*.
- Ikovenko, S., 2004. TRIZ and Computer Aided Inventing. In *Building the Information Society*. pp. 475–485.
- Kevser Coşkuna; M. Cem Altun, 2013. A Conceptual Model for Improving In-Situ Construction Techniques Using Triz and Six Sigma Approaches. In *Research, Development, and Practice in Structural Engineering and Construction*.
- Książek, M.V. et al., 2015. Computer-aided decision-making in construction project development. *Journal of Civil Engineering and Management*.
- Kulatunga, U., Amaratunga, R. & Haigh, R., 2006. Construction innovation: a literature review on current research. , pp.654–662.
- Kwon, D.Y., Gross, M.D. & Yi-Luen Do, E., 2009. ArchiDNA: An interactive system for creating 2D and 3D conceptual drawings in architectural design. *CAD Computer Aided Design*.
- Laefer, D.F. & Truong-Hong, L., 2017. Toward automatic generation of 3D steel structures for building information modelling. *Automation in Construction*.
- Lee D., Shin.S., 2015. High tensile UL700 frame module with adjustable control of length and angle. *Journal of Constructional Steel Research*, 106, pp.246–257.
- Lee, D. & Shin, S., 2014. Advanced high strength steel tube diagrid using TRIZ and nonlinear pushover analysis. *Journal of Constructional Steel Research*, 96, pp.151–158.
- Lin, Y.H. Lee, P.C., 2005. Applying TRIZ to the construction industry. In *10th International Conference on Civil, Structural and Environmental Engineering Computing, Civil-Comp 2005*. Rome, p. 12.
- Luo, Y., Shao, Y. & Chen, T., 2012. Study of New Wall Materials Design Based on TRIZ Integrated Innovation Method. *Management Science and Engineering*, 6(4),

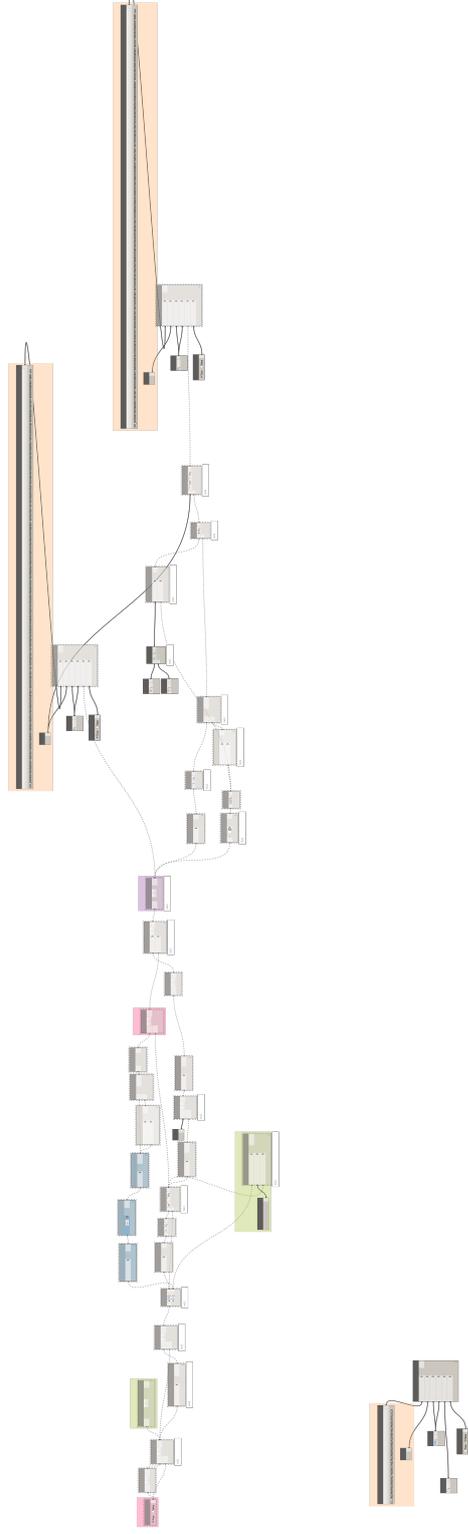
- pp.15–29.
- Mao, X., Zhang, X. & AbouRizk, S.M., 2009. Enhancing Value Engineering Process by Incorporating Inventive Problem-Solving Techniques. *Journal of Construction Engineering and Management*, 135(5), pp.416–424.
- Mohamed, Y., 2002. *A Framework for systematic improvement of construction systems*. University of Alberta.
- Mohamed, Y. & AbouRizk, S., 2005. Application of the Theory of Inventive Problem Solving in Tunnel Construction. *Journal of Construction Engineering and Management*, 131(10), pp.1099–1108.
- Negendahl, K., 2015. Building performance simulation in the early design stage: An introduction to integrated dynamic models. *Automation in Construction*.
- Nembrini, J., Samberger, S. & Labelle, G., 2014. Parametric scripting for early design performance simulation. *Energy and Buildings*.
- NIMBS Committee, 2007. National Building Information Modeling Standard. *Nbim*, p.180.
- Nimtawat, A. & Nanakorn, P., 2009. Automated layout design of beam-slab floors using a genetic algorithm. *Computers and Structures*.
- León-Rovira, N., 2001. A proposal to integrate TRIZ and CAD (Computer Aided TRIZ-based Design). In *TRIZCON 2001*.
- “Open Source Graphical Programming for Design.” Dynamo BIM, dynamobim.org. [Accessed October 22, 2018]
- Østergård, T., Jensen, R.L. & Maagaard, S.E., 2017. Early Building Design: Informed decision-making by exploring multidimensional design space using sensitivity analysis. *Energy and Buildings*.
- Ozorhon, B. et al., 2010. Innovation in Construction: A Project Life Cycle Approach. *SCRI Research Report 4*, (May).
- Paul, N. & Borrmann, A., 2009. Geometrical and topological approaches in building. *Electronic Journal of Information Technology in Construction*.
- Petersen, S. & Svendsen, S., 2010. Method and simulation program informed decisions in the early stages of building design. *Energy and Buildings*.
- Retseptor, G., 2005. 40 Inventive Principles in Marketing, Sales and Advertising. *the TRIZ journal*.
- Robertson, B.F. & Radcliffe, D.F., 2009. Impact of CAD tools on creative problem solving in engineering design. *CAD Computer Aided Design*.
- Rosa, F., E. Rovida, and R. Viganò. “Approach to an Integration of Triz and Heuristic Methods for the Development of Industrial Products.” *Proceedings of AEDS 2006 Workshop 2006*, 89–95.
- Rosa, Francesco, Gaetano Gascini, and Alessandro Baldussu. “UNO-BID: Unified Ontology for Causal-Function Modeling in Biologically Inspired Design.” *International Journal of Design Creativity and Innovation 2015*, 177–210.
- Sacks, R. et al., 2010. Interaction of Lean and Building Information Modeling in Construction. *Journal of Construction Engineering and Management*.
- Salamatov, Y., 2005. *TRIZ: the right solution at the right time: a guide to innovative problem solving* 2nd ed.,

- Shao-tsai Cheng, Wen-der Yu, Chih-ming Wu, Ruey-sen Chiu., 2009. Analysis of construction inventive patents based on TRIZ. In *Proceedings of the International Symposium on Automation and Robotics in Construction and Mining*. pp. 1–6.
- Shaughnessy, J., 1947. *Research methods in psychology* 9th ed.,
- Song, S., Yang, J. & Kim, N., 2012. Development of a BIM-based structural framework optimization and simulation system for building construction. *Computers in Industry*.
- Teplitskiy, A., 2005a. Application of 40 Inventive Principles in Construction. *The TRIZ journal*, pp.1–23.
- Teplitskiy, A., 2005b. Application of Inversion Effect in Construction. *The TRIZ journal*, pp.1–8.
- Teplitskiy, A., 2005c. Solving Technical Contradictions in Construction with Examples. *The TRIZ journal*.
- Toole, T.M., 2001. Technological Trajectories of Construction Innovation. *Journal of Architectural Engineering*, 7(4), pp.107–114.
- TRIZ Research Team, 2009. DSDI TRIZ. *POSCO online news*. Available at: <http://www.posco.co.kr/homepage/docs/kor/jsp/news/posco/s91fnews002p.jsp?idx=186751;2009> [Accessed April 20, 2015].
- Tuhus-Dubrow, D. & Krarti, M., 2010. Genetic-algorithm based approach to optimize building envelope design for residential buildings. *Building and Environment*.
- Wu, C.-M., Yu, W.-D., & Cheng, S.-T., A model used for the generation of innovative construction alternatives.
- Y.H. Lin, P.C. Lee., 2005. Applying TRIZ to the construction industry. In *Proceedings of the Tenth International Conference on Civil, Structural and Environmental Engineering Computing*. Civil-Comp Press, Stirlingshire, UK.
- Yalcinkaya, M. & Singh, V., 2015. Patterns and trends in Building Information Modeling (BIM) research: A Latent Semantic Analysis. *Automation in Construction*.
- Yang, C.-L., 2013. Using Modified TRIZ Approach for Quality Improvement. *Science Journal of Business and Management*, 1(1), p.14.
- Yang, J., Baeg, H. & Moon, S., 2014. Utilization of contradiction for creating design alternatives in construction value engineering. *KSCE Journal of Civil Engineering*, 18(2), pp.355–364.
- Yu W.-D., Wu C.-M., Huang.T.-W., 2009. Development and application of a systematic innovation procedure for construction technology. In *2009 26th International Symposium on Automation and Robotics in Construction, ISARC*. pp. 149–159.
- Yu, W.-D., Wu, C.-M. & Lien, W.-C., 2008. Fast innovation of construction technologies with computer aided innovation tools. In *The 25th International Symposium on Automation and Robotics in Construction. ISARC-2008*. Vilnius Gediminas Technical University Publishing House Technika, pp. 521–527.
- Yu, W. Der et al., 2012. A self-evolutionary model for automated innovation of construction technologies. *Automation in Construction*, 27, pp.78–88.
- Zhang, X., Mao, X. & AbouRizk, S.M., 2009. Developing a knowledge management

system for improved value engineering practices in the construction industry. *Automation in Construction*, 18(6), pp.777–789.

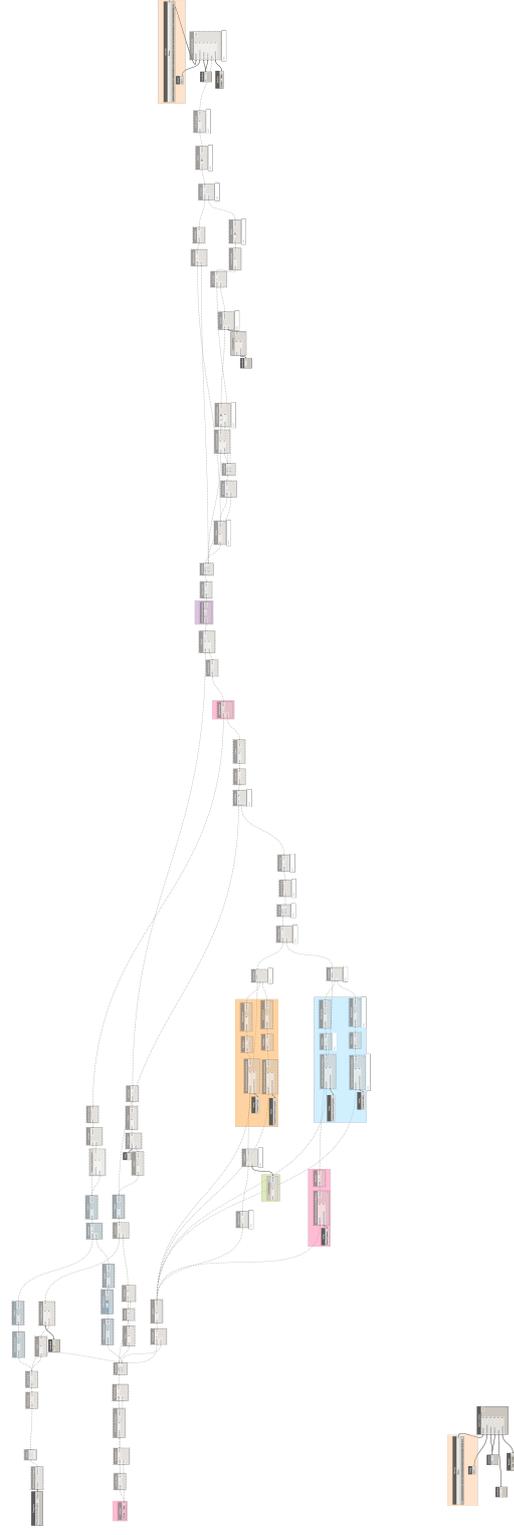
Appendices

Appendix A "Graphical program for the Interaction Matrix creation"



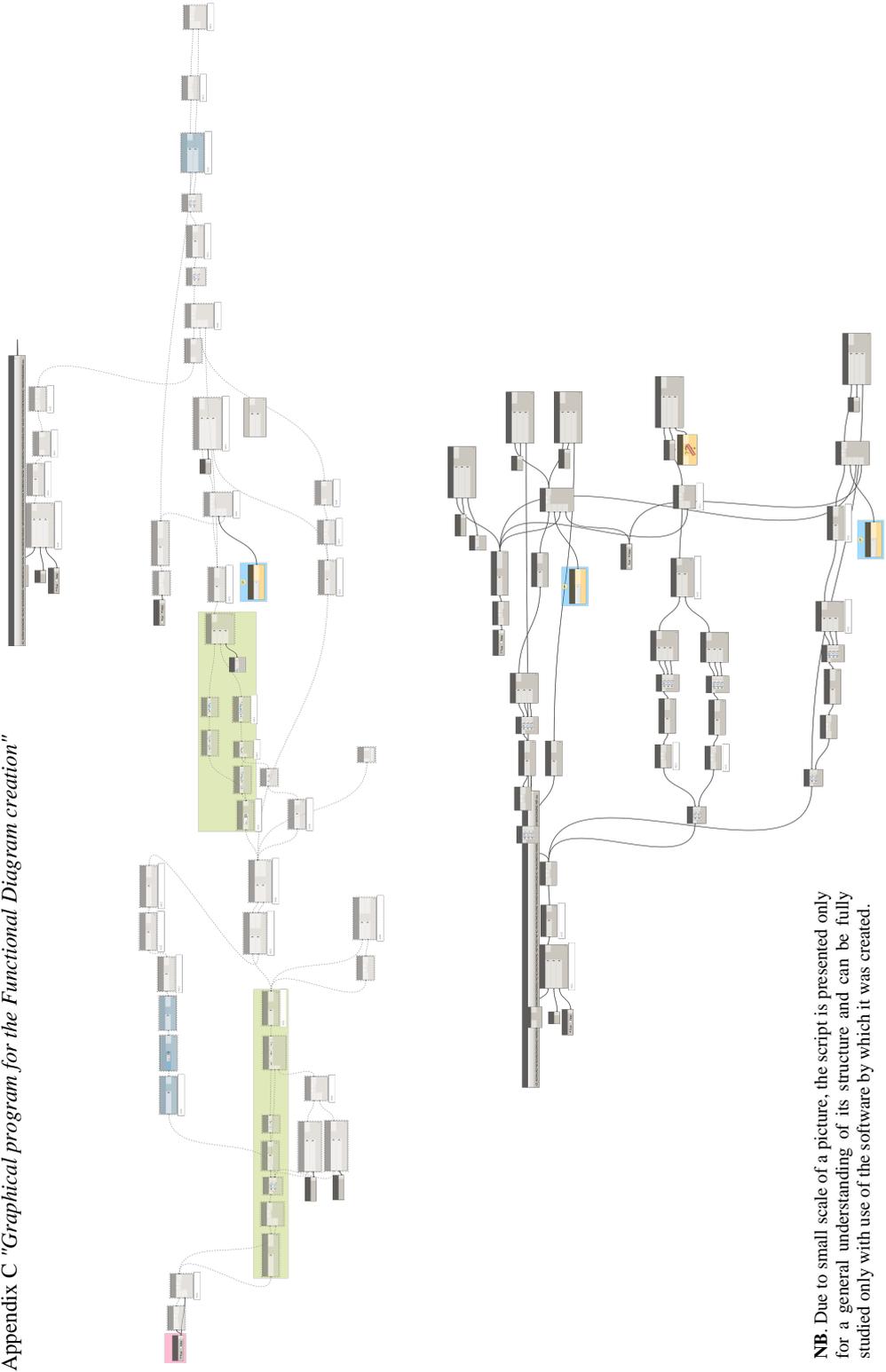
NB. Due to small scale of a picture, the script is presented only for a general understanding of its structure and can be fully studied only with use of the software by which it was created.

Appendix B "Graphical program for the Matrix of Functions creation"



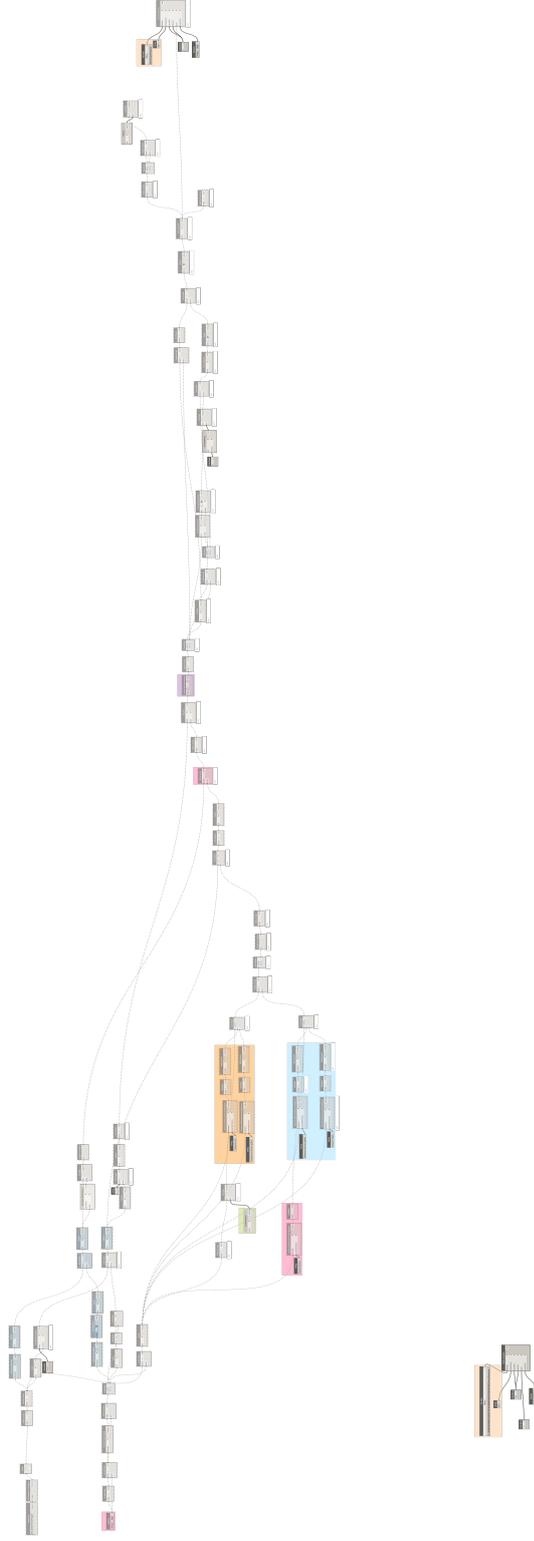
NB. Due to small scale of a picture, the script is presented only for a general understanding of its structure and can be fully studied only with use of the software by which it was created.

Appendix C "Graphical program for the Functional Diagram creation"



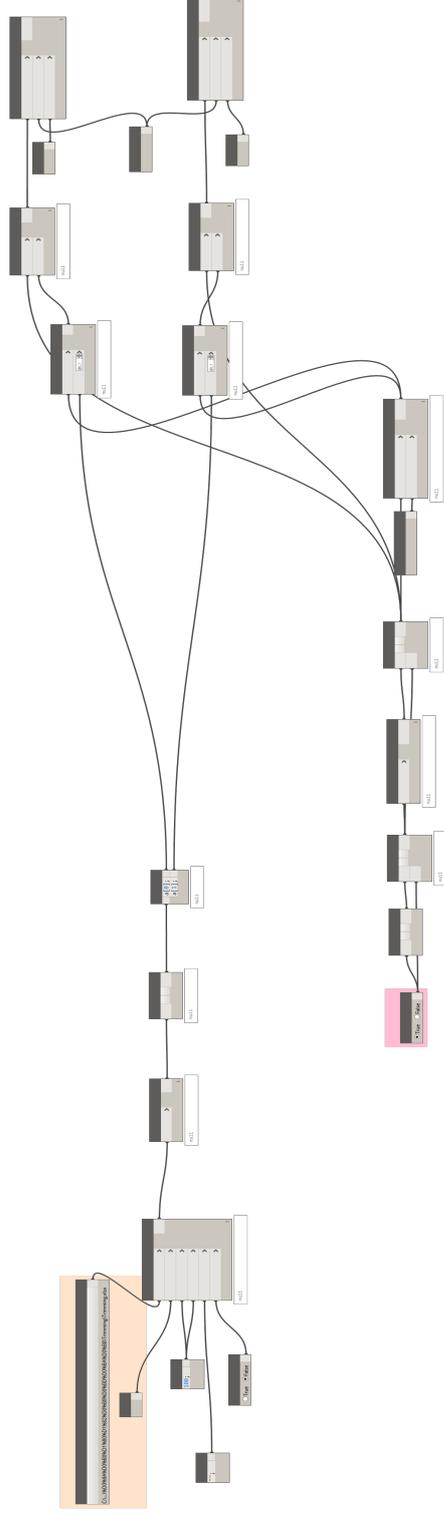
NB. Due to small scale of a picture, the script is presented only for a general understanding of its structure and can be fully studied only with use of the software by which it was created.

Appendix D "Graphical program for Ranking of the BIM model's elements"



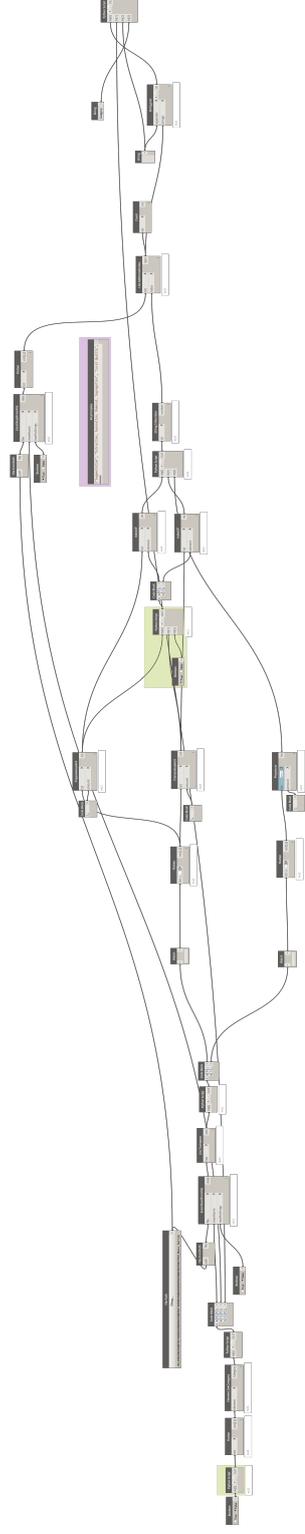
NB. Due to small scale of a picture, the script is presented only for a general understanding of its structure and can be fully studied only with use of the software by which it was created.

Appendix E "Graphical program for Trimming of the BIM model's elements"



NB. Due to small scale of a picture, the script is presented only for a general understanding of its structure and can be fully studied only with use of the software by which it was created.

Appendix F "Graphical program for the Contradiction Analysis of the BIM model's elements"



NB. Due to small scale of a picture, the script is presented only for a general understanding of its structure and can be fully studied only with use of the software by which it was created.

Appendix G *“The inventive solutions (principles) that may guide to elimination of the technical contradiction for the element of the BIM model”*

1. Segmentation

- 1) *Divide an object into independent parts.*
- 2) *Make an object easy to disassemble.*
- 3) *Increase the degree of fragmentation or segmentation.*

2. Taking out

- 1) *Separate an interfering part or property from an object, or single out the only necessary part (or property) of an object.*

3. Local quality

- 1) *Change an object's structure from uniform to non-uniform, change an external environment (or external influence) from uniform to non-uniform.*
- 2) *Make each part of an object function in conditions most suitable for its operation.*
- 3) *Make each part of an object fulfill a different and useful function.*

4. Asymmetry

- 1) *Change the shape of an object from symmetrical to asymmetrical.*
- 2) *If an object is asymmetrical, increase its degree of asymmetry.*

5. Merging

- 1) *Bring closer together (or merge) identical or similar objects, assemble identical or similar parts to perform parallel operations.*
- 2) *Make operations contiguous or parallel; bring them together in time.*

6. Universality

- 1) *Make a part or object perform multiple functions; eliminate the need for other parts.*

7. “Nested doll”

- 1) *Place one object inside another; place each object, in turn, inside the other.*
- 2) *Make one part pass through a cavity in the other.*

8. Anti-weight

- 1) *To compensate for the weight of an object, merge it with other objects that provide lift.*
- 2) *To compensate for the weight of an object, make it interact with the environment (e.g. use aerodynamic, hydrodynamic, buoyancy and other forces).*

9. Preliminary anti-action

- 1) *If it is necessary to do an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects.*
- 2) *Create beforehand stresses in an object that will oppose known undesirable working stresses later on.*

10. Preliminary action

- 1) *Perform, before it is needed, the required change of an object (either fully or partially).*
- 2) *Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.*

11. Beforehand cushioning

- 1) *Prepare emergency means beforehand to compensate for the relatively low reliability of an object.*

12. Equipotentiality

- 1) *In a potential field, limit position changes*

13. 'The other way round'

- 1) *Invert the action(s) used to solve the problem*
- 2) *Make movable parts (or the external environment) fixed, and fixed parts movable.*
- 3) *Turn the object (or process) 'upside down'.*

14. Spheroidality – Curvature

- 1) *Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures.*
- 2) *Use rollers, balls, spirals, domes.*

15. Dynamics

- 1) *Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition.*
- 2) *Divide an object into parts capable of movement relative to each other.*
- 3) *If an object (or process) is rigid or inflexible, make it movable or adaptive.*

16. Partial or excessive actions

- 1) *If 100 percent of an object is hard to achieve using a given solution method then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve.*

17. Another dimension

- 1) *To move an object in two- or three-dimensional space.*

- 2) *Use a multi-story arrangement of objects instead of a single-story arrangement.*
- 3) *Tilt or re-orient the object, lay it on its side.*
- 4) *Use 'another side' of a given area.*

18. Mechanical vibration

- 1) *Cause an object to oscillate or vibrate.*
- 2) *Increase its frequency (even up to the ultrasonic).*
- 3) *Use an object's resonant frequency.*

19. Periodic action

- 1) *Instead of continuous action, use periodic or pulsating actions.*
- 2) *If an action is already periodic, change the periodic magnitude or frequency.*
- 3) *Use pauses between impulses to perform a different action.*

20. Continuity of useful action

- 1) *Carry on work continuously; make all parts of an object work at full load, all the time.*
- 2) *Eliminate all idle or intermittent actions or work.*

21. Skipping

- 1) *Conduct a process, or certain stages at high speed.*

22. "Blessing in disguise"

- 1) *Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect.*
- 2) *Eliminate the primary harmful action by adding it to another harmful action to resolve the problem.*
- 3) *Amplify a harmful factor to such a degree that it is no longer harmful.*

23. Feedback

- 1) *Introduce feedback (referring back, cross-checking) to improve a process or action.*
- 2) *If feedback is already used, change its magnitude or influence.*

24. Intermediary

- 1) *Use an intermediary carrier article or intermediary process.*
- 2) *Merge one object temporarily with another (which can be easily removed).*

25. Self-service

- 1) *Make an object serve itself by performing auxiliary helpful functions*
- 2) *Use waste resources, energy, or substances.*

26. Copying

- 1) *Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies.*
- 2) *Replace an object, or process with optical copies.*
- 3) *If visible optical copies are already used, move to infrared or ultraviolet copies.*

27. Cheap short-living objects

- 1) *Replace an inexpensive object with a multiple of inexpensive objects, comprising certain quality.*

28. Mechanical substitution

- 1) *Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means.*
- 2) *Use electric, magnetic and electromagnetic fields to interact with the object.*
- 3) *Change from static to movable fields, from unstructured fields to those having structure.*
- 4) *Use fields in conjunction with field-activated (e.g. ferromagnetic) particles.*

29. Pneumatics and hydraulics

- 1) *Use gas and liquid parts of an object instead of solid parts.*

30. Flexible shells and thin films

- 1) *Use flexible shells and thin films instead of three dimensional structures*
- 2) *Isolate the object from the external environment using flexible shells and thin films.*

31. Porous materials

- 1) *Make an object porous or add porous elements.*
- 2) *If an object is already porous, use the pores to introduce a useful substance or function.*

32. Colour changes

- 1) *Change the color of an object or its external environment*
- 2) *Change the transparency of an object or its external environment.*

33. Homogeneity

- 1) *Make objects interacting with a given object of the same material (or material with identical properties).*

34. Discarding and recovering

- 1) *Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.*
- 2) *Conversely, restore consumable parts of an object directly in operation.*

35. Parameter changes

- 1) *Change an object's physical state.*
- 2) *Change the concentration or consistency.*

- 3) *Change the degree of flexibility.*
- 4) *Change the temperature.*

36. Phase transitions

- 1) *Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).*

37. Thermal expansion

- 1) *Use thermal expansion (or contraction) of materials.*
- 2) *If thermal expansion is being used, use multiple materials with different coefficients of thermal expansion.*

38. Strong oxidants

- 1) *Replace common air with oxygen-enriched air.*
- 2) *Replace enriched air with pure oxygen.*
- 3) *Expose air or oxygen to ionizing radiation*
- 4) *Use ionized oxygen.*
- 5) *Replace ozonized (or ionized) oxygen with ozone.*

39. Inert atmosphere

- 1) *Replace a normal environment with an inert one.*
- 2) *Add neutral parts, or inert additives to an object.*

40. Composite materials

- 1) *Change from uniform to composite (multiple) materials.*

Publication I

Renev I., Chechurin L.

Application of TRIZ in Building Industry: Study of Current Situation

Reprinted with permission from
Procedia CIRP

Vol. 39, pp. 209-215, 2016

© 2016, Elsevier



TFC 2015 – TRIZ FUTURE 2015

Application of TRIZ in building industry: study of current situation

Ivan A. Renev^{a,*}, Leonid S. Chechurin^a

^aLappeenranta University of Technology LUT, Skinnarilankatu 34,53850 Lappeenranta, Finland

* Corresponding author. Tel.: +7-921-560-7350 ; E-mail address: msc.irenev@gmail.com

Abstract

This article is focused on literature review in the area of TRIZ application in building industry. TRIZ is the Russian acronym for the Theory of Inventive Problem Solving which can be presented as a methodology for problem-solving, ideas-generating and forecasting in innovation, based on logic and data. The theory has been widely used in many fields since early 2000s when innovation became an integral part of the modern World. Despite that, the analysis showed that the number of publications related to application of TRIZ in construction is less than 2% out of all TRIZ-related studies in the SCOPUS database. The paper is organized in the following order: introduction into the topic, the principle of obtaining the dataset for the review, Short description of TRIZ and its possible application in construction, discussion of demand of innovation in building industry and the main body consisting of TRIZ in Development of Construction Techniques and Technologies, TRIZ in Design of New Structures and Construction Materials and TRIZ in Construction Project Management and Value Engineering. The work ends with conclusion, suggestion for future work and acknowledgment. Overall, 28 scientific works regarding application of TRIZ in building industry were discovered and reviewed in this paper. The study reveals that TRIZ usage in construction is still quite limited. The further research will adapt classic TRIZ tools for construction engineering and management and provide a number of specific case studies.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of Scientific committee of Triz Future Conference

Keywords: TRIZ; building industry; construction; innovation.

1. Introduction

Construction engineering and construction management are professional disciplines within building industry which deal with design, overall planning, construction and management of infrastructures (buildings, bridges, utilities, etc.). To succeed in those aspects construction specialists have to always find new solutions and ideas, solve technical and technological issues which may appear in every single project's stage during both design and construction. Thanks to bright innovative ideas and solutions, which enable the scientists and engineers to evolve construction materials, technologies, design techniques, etc., the World nowadays has such truly astonishing structures as the Dubai's Burj Khalifa (the tallest man-made structure in the world, standing at 829,8 m), the Sidu River Bridge in China (the bridge with the biggest drop distance from the bridge deck to the ground level which is nearly 500m high and crosses a mountain belt), the incredible Milau Viaduct in France (the world's tallest bridge with one mast reaching 343 meters above the base of the

structure), the China's Jinping-I Dam (the tallest dam 305m high), the Capital Gate tower (the World's furthest leaning skyscraper in Abu Dhabi that was built to lean 18°) and a few others. Moreover, there are quite simple structures differing by the way they were built. For instance, a Chinese construction company used a Modular method and became the world's fastest builder after erecting a 57-storey skyscraper in 19 working days in central China [1]. The method enables the builders to assemble the prefabricated blocks (modules) instead of building brick by brick.

In the modern professional world engineers and managers must have a universal intellectual set of tools that would enable them to find the right ideas in a well-structured methodological way avoiding consideration of knowingly false solutions leading to waste of time, missed deadlines, planned budgets, etc. Since the risk of failure in construction is higher than in many other industries [2] it is not acceptable to use trial-and-error approach (especially for large-scale projects) to find ideas and solutions for the development and improvement of design procedures, structures and

construction techniques. At the same time, there is the Theory of inventive problems solving (TRIZ) which includes a practical methodology, tool sets, a knowledge base, and model-based technology for generating new ideas and solutions for problem solving [3]-[5]. According to ETRIA (the European TRIZ association) Worldwide survey performed in 2009 [6], only 3,5% of construction professionals are devoted to the TRIZ, which means that TRIZ remains marginal in the building industry. This paper presents scientific indexed literature review to a) identify existing innovative approaches based on TRIZ tools which find their application in design and construction and help solving ongoing issues, b) justify relevance of further study of TRIZ application in building industry and, finally, develop a set of key objectives to be later investigated.

2. Creating the dataset

The review is based on papers indexed by SCOPUS mostly database. In order to create the set of articles to be reviewed, two searches were performed: (1) the search query "TRIZ" and "Construction" in Title or Abstract or Keywords and (2) "TRIZ" and "Building" in Title or Abstract or Keywords. The terms "Construction" and "Building" were selected as they are most commonly used in the studied field while "TRIZ" as generally accepted abbreviation for the Theory of Inventive Problem Solving. The former case resulted in 83 papers while the latter in 57 ones. However, reading the papers filtered out the irrelevant texts that reduced the quantity to only 18 and 6 industry-related articles respectively with 2 of them being in both lists. Thus, the dataset consists of 22 articles selected from the SCOPUS database. It is just 2% of the 1389 articles retrieved by "TRIZ" in Title or Abstract or Keywords search. Quick analysis shows that 9 of articles are cited more than once. Most of the works originated from the PRC during the last decade. As the amount of retrieved papers is small, the Google finder was used to extend the list of reviewed papers. The search query "TRIZ" and "Construction" and "Building" forwarded us to such sources as ScienceDirect, Elsevier and Springer where 6 more industry-related papers were obtained. All bibliographic information is given as it was seen in May 2015. Thus, 28 works regarding application of TRIZ in construction were discovered and reviewed in this paper, some of which are available in abstracts only. The review showed that those articles are mostly dedicated to:

- Development of Construction Techniques and Technologies
- Design of New Structures and Construction Materials
- Construction Project Management and Value Engineering

3. Demand of Innovation in Construction

First, we need to comment the demand for innovation in construction in general. According to [8] innovation can be defined as "the successful exploitation of new ideas. However, ongoing research [2], [9]-[12] and statistical data [6], [8] show that construction lags behind many other

industrial sectors (such as IT, computers, software, automotive industry, electronics, mechanical engineering, etc.) in terms of efficiency and productivity due to mostly lack of realizations of new ideas.

For instance, U. Kulatunga et al. demonstrate [2] that construction is behind other industrial sectors due to, in particular, lack of innovations. At the same time modern construction companies are keen on innovations to be competitive on the market, which is why engineers and managers innovate when technology can be modified easily. On the other hand, construction industry is also known for its conservatism and professionals tend to use an accepted industry practice and norms in fulfilling client's need.

The study [11] by S. Asad et al. also shows the importance of innovations for construction organizations. The authors even claim that construction innovations can become a fourth dimension in the future along with the traditional dimensions of cost, quality and time. Only in that case such organizations would be able to take advantage of changes in market economy. The study [13] additionally explains that successful building products must be innovative to become competitive on the market in terms of cost, time and performance efficiency. Besides, the survey performed by the Chartered Institute of Building (UK) [8] discovered that 100% of respondents felt that innovation is important for the future of construction.

To sum up, there is plenty of research, surveys and literature regarding innovation in construction and almost all of them state that innovations are vital in construction sector but the question is how to become innovative. Z. Ding and J. Ma [14] describe that using TRIZ can accelerate technical innovations in construction process. On the other hand, the report [6] shows the statistical data related to distribution of TRIZ use in industrial sectors which demonstrate that TRIZ is not widely used in civil engineering and building industry. The other work [15] by D. M. Conall and Ó. Catháin explains again that construction specialists in most cases do not use systematic or formal design methods and this situation leads to a number of drawbacks (for instance, it takes a long time to find a solution; waiting for inspiration; designers cannot proceed in a logical manner, etc.). To avoid such minuses a systematic innovation approach was suggested, which came out of TRIZ. The approach is based on five principles called "pillars" which are function, contradiction, resources, ideality and interfaces.

Furthermore, Y. Mohamed and S. AbouRizk [16]-[18] noticed that there is lack of structured theory for managing innovation improvement in the construction industry. Innovation is an integral part of improvement of construction techniques but, however, most approaches are based on the trial-and-error method. The studies present a few number of cases to show results of TRIZ application in tunnel construction. All case studies were taken from real life situations and it was well proven that TRIZ tools help to achieve innovative conceptual solution in a methodological way avoiding consideration of irrelevant results.

Ding Z. et al. [10] particularly suggest the design framework of the technology innovation platform based on TRIZ by taking advantage of available patent knowledge in the construction industry. Based on extracted construction patent knowledge, the development of construction technology innovation platform allows a heuristic environment to help the industry improve the capacity and efficiency by motivating knowledge worker's innovative thinking.

Therefore, it can be concluded that innovation must be of high demand in the construction industry but, at the same time, construction is considered slower in technology innovation in the past decades partially due to the characteristics of the industry. The literature review clearly states that it is necessary to extend application of innovations in construction and determine an optimal approach for ideas generation to be applied in a real practice

4. TRIZ in Development of Construction Techniques and Technologies

A small amount of research has been done regarding the development of construction techniques and technologies using TRIZ. For instance, the article [19] describes step-by-step analysis of formwork technology development from the TRIZ point of view. The 40 inventive principles are used for formwork patents investigation. Based on 176 Taiwan patents analysis from years 1975 to 2005 there were extracted top 5 inventive principles which were most frequently used in the formwork patents. The principles are: (1) prior action, (2) Combining, (3) Segmentation, (4) Cushion in advance and (5) Mediator. Some examples of each of them are given in the work to show the formwork technology development. To predict future development trends, the contradiction matrix was used, which led to determination of future innovation trends of formwork engineering. Among those trends are the following inventive principles: Inversion, Segmentation, Transformation of properties, Replacement of mechanical system and Extraction. Finally, it was concluded that TRIZ provides a systematic approach for technology research, and construction technologies can be analyzed with TRIZ.

Yu W.-D. and Wu C.-M. also state that construction technologies are little comparable to other industries due to lack of innovation tools [20], [21]. They proposed to use a Systematic Technology Innovation Procedure (STIP) for fast innovation in construction technologies. The STIP approach is also based on patent analysis, TRIZ and Computer Aided Invention (CAI) tools. STIP consist of (1) a problem description scheme, (2) a systematic procedure of technology innovation and (3) a set of criteria for technology evaluation. STIP principal scheme is: PROBLEM->DEFINITION->ANALYSIS->SOLUTION (using TRIZ)->APPROVAL->INNOVATIVE TECHNOLOGY. A case study of STIP application in searching an innovative solution for leaking pipes surrounded with reinforced concrete (RC) is provided as an example.

Furthermore, the same authors developed their research in [22]. They explained that technology innovation has been an important source of competitiveness for individual construction firms and provide long term benefits for the industry. In this research they proposed a new integrative "Model Used for the Generation of Innovative Construction Alternatives" (MUGICA) based on the formerly developed STIP and the "Model for Automated Generation of Innovative Alternatives" (MAGIA) to tackle both the systematic and automated requirements of construction technology innovation. The testing result showed that the proposed MUGICA was able to improve both the efficiency and effectiveness of construction technology innovation compared to previous approaches.

According to Kevser Coşkuna and M. Cem Altun [23] in-situ construction techniques have distinct characteristics such as unique production, partial lack of industrialization, standardization and quality control, location of construction process, local techniques related to construction culture. Those characteristics are mostly reducing "productivity". There are several innovation models for improving the "quality" in the construction process. The authors found out that TRIZ could be used to improve the quality of in-situ construction techniques. However, it was discovered that improvements are needed to the "analysis of the problem" and "evaluating proposed solutions" steps of the TRIZ approach. According to the comprehensive investigation of other improvement methods, the Six Sigma approach was found to be effective in overcoming the uncertainties in TRIZ. In the paper a conceptual model for improving in-situ construction techniques is proposed by using the TRIZ approach, the Six Sigma approach and statistical tools. It was demonstrated that the integration of TRIZ and Six Sigma approaches is considerably more effective. The same authors evolved their research in [24] and also investigated the applicability of the TRIZ tools on in-situ construction technologies. Improving the quality of the construction technique for wood joint fixing is defined as a problem to be tackled. The problem was solved with TRIZ method considering "construction time" and "strength" criteria. For the assessment of the method, construction process observation and compressive strength tests were carried out.

Lin Y.H. and Lee P.C. presented a modified TRIZ model called TRIZ-AHP-G model which combines with Analytic Hierarchy Process (AHP) and grey relational analysis [25]. The use of TRIZ-AHP-G model was illustrated by two examples, the pre-stressed concrete and the shoring system. The results of both examples demonstrated the effectiveness of this proposed model, which can effectively measure the importance of criteria associated with innovating products based on expert knowledge.

5. TRIZ in Design of New Structures and Construction Materials

TRIZ has also shown its potential in design of new structures and construction materials. One of such examples is

an integrated innovation method combining TRIZ, Technology Acceptance Method (TAM-approach for product demand analysis) and Quality Function Deployment (QFD - transforms customer or market demands into design requirements) suggested in the work [26] by Y. Luo et al. The approach helps to solve main contradiction problems from the product demand analysis to its design, production and application. An example for design of new wall material using integrated method was given in the paper. The core part of the method is identification and solving contradictions in customer demand and quality control during design and production procedures using different TRIZ tools. As for building façade solutions, Chen Z. et al. proposed in [27] a TRIZ based management process model for selecting the most appropriate solutions of building façades. To set up the model, environmental values of building façades were analyzed with respect to their life-cycle performance and impacts.

Besides that, TRIZ can be applied in finding inventive ways to upgrade heat insulation of external building structures. R. Sen Chiu and S. T. Cheng [28] describe how solar reflectance of heat-proof paint was improved by applying TRIZ contradiction. The parameters which were discovered to be improved are the following: temperature, harmful elements on objects, adaptability, stability of objects and brightness. To solve those five contradictions, four inventive principles (transformation of the physical and chemical states of an object, segmentation, changing the color and flexible membranes or thin film) were singled out in TRIZ. A number of heat resistance tests were performed, which led to successful development of new paint that upgrades the solar reflectance and heat insulation of the plate paint and, thus, saves over 24% of electricity for internal air conditioning.

The other study [29] by D. Lee and S. Shin shows how TRIZ can be used when it is required to evaluate bearing steel diagrid structures of free-shaped tall buildings to resolve such issues as the concentration of stress at the ends of the tube contacted to cap plates. Stress concentrations among node rib, cap plate and tube result in collapses of tubes before tubes arrive to yielding stress state. This occurs despite using cap plates, like as changing thickness and extended length. In addition, an extended cap plate may cause interference in building construction. In this study a DSDI TRIZ procedure was mainly applied in order to develop the details of diagrid structures. The DSDI (for "Define", "Solve", "Design", and "Implement") approach was introduced by a POSCO steel company in 2008 [30]. In the "Define" stage it is required to define the above-mentioned problem of the existing diagrid detail. It was found that stresses by high performance steel tube with tensile stress of 800 MPa have to be bigger than stresses by given forces at the zone of the tube in which the tube contacts the cap plate in order to avoid collapse. Inventive ideas were evaluated by solving the problem that exists in the operating zone. Since the diameter and thickness of each tube are constant for the purpose of economy, they could not be considered to be design variables in the operating zone. Cap plate and node rib are design variables and can be

modified to improve the existing diagrid details. To solve the problem and generate inventive ideas the authors considered a multi-screen thinking method, a resource analysis and interaction matrix. To resolve technical and physical contradictions, separation in space and based upon condition were applied to idea generation. As a result, the cap plate was modified to both enlarge the contact area between a tube and a cap plate and reduce the interference that results from length extensions of a cap plate. Therefore, original flat cap plates were developed to be either concave or convex shaped plates. The "Design and Implement" stages of DSDI TRIZ procedures measure the idea generation results by using measurable tools such as structural analyses or experiments. In the particular case the researchers applied ABAQUS to investigate structural behaviors of the invention results. A convex diagrid was evaluated as being an improvement on the current best solution. TRIZ applications shown in this study verify that TRIZ is a strong idea generation tool for conceptual design to improve current steel-framed products such as diagrid structures in tall buildings. Another research related to TRIZ usage in steel bearing structures design was presented by D. Lee and S. Shin in [31] where they suggested developing an advance in the frame modules and frame structures used to truss structures. The DSDI approach was also used to verify that the advanced product secures structural safety and is of optimized size.

Craig et al. suggested applying so-called BioTRIZ approach for radiative cooling of buildings [32]. BioTRIZ is a combination of TRIZ and Biomimetics - methodology for using Principles of Nature in problem solving and design. BioTRIZ matrix was applied in order to design roofs for buildings in hot climates that get free cooling through radiant coupling with the sky. The chosen solution is to replace the standard insulation component with an open cell honeycomb. The vertical cells allow longwave radiation to pass, while stopping convection.

6. TRIZ in Construction Project Management and Value Engineering

The key target of Construction Project Management (CPM) is satisfaction of a customer, codes and regulations to deliver a qualitative, safe, secure and financially effective project that meets the designed time schedule and budget. Hence, in order to achieve those goals specialists have been applying various techniques to managing a complex construction process. Since the level of competitiveness and complication of projects have been increasing, the majority of such techniques cannot be considered beneficial nowadays. Several papers were discovered during literature review regarding the above mentioned subtopic. For instance, Cabrera B. R. and Li G.J. [33] suggest more effective construction process via application the key TRIZ tool such as the contradiction matrix in order to develop innovative solutions to the most complex issues. As a practical example, the case study based on application of TRIZ tools in a highway construction was discussed. The abovementioned tools assist optimization of

working method for soil grading and compacting. However, the authors noticed that the innovative solution, after some time of testing, would possibly create new issues which should be further reevaluated with the help of TRIZ techniques and common practice. Moreover, the authors concluded that all project's participants have to always accurately investigate and discuss created inventive solutions before applying them into practice. H. Cui [34] presented conflict resolution methods for construction projects from the standpoint of TRIZ. Based on the review of the article abstract, the main TRIZ tools used were: the ideal final result (IFR), Substance-Field (Su-Field) analysis, 76 standards, separation principles, contradiction matrix and 40 inventive principles. Case studies of key conflicts limiting the IFR were discussed in details. Additionally, a few specific solutions for the physical and technical contradictions in the construction projects were presented with the illustration of conflict resolutions as a case. Chang P.-L. et al. [35] developed and tested a preliminary Model of Engineering Problem Solver (MEPS) based on TRIZ to explore the underlying patterns of problem solving for emergent construction problems. MEPS consists of 15 identified management parameters, a contradiction matrix and 16 problem-solving principles. Their work received further development in [36] where a General Construction Problem-Solving Model (GCPM) was presented. The proposed GCPM integrates Construction Project Management Body of Knowledge (CPMBOK), TRIZ and Data Mining (DM), so that the management parameters (MP) and Problem-Solving Principles (PSP) are defined and derived. The model is to assist the construction engineers in solving various emergent problems they encounter daily.

Along with amelioration of conflict resolution methods for construction projects using TRIZ, a number of steps towards improvement of value engineering (VE) in construction were taken as well. One of such attempts was, for instance, performed by Mao X. et al. [37]. The paper presents a value engineering knowledge management system (VE-KMS), which applies TRIZ and integrates its tools into the creativity phase of the VE process and, hence, makes the creativity phase more systematic, organized and problem-focused. Procedures of the improved VE creativity phase consist of the following steps: (1) collect project explicit knowledge and VE team information, (2) break project into subsystems, (3) identify harmful functions in each subsystem Function (using TRIZ function analysis), (4) identify and solve technical contradictions (the TRIZ contradiction matrix), (5) identify and solve physical contradictions (four general separation principles to solve physical contradictions: (a) separation in time, (b) separation in space, (c) separation between the whole system and its parts, and (d) separation based on different conditions), (6) conduct substance-field analysis, (7) improve the project according to technological evolution trends (using TRIZ nine evolution patterns). The direction regarding value engineering in construction was developed by the same scientists in their following work [38] where they explored the possibility of incorporating TRIZ into the workshop session of the value engineering exercise by initiating three new

procedures in this session: (1) an initial design procedure to examine the functions of a proposed project; (2) a function trimming procedure to fully utilize existing resources and ensure low life-cycle cost and sustainability of the proposed project; and (3) an interaction analysis procedure to assess the proposed project in a broad perspective with social, economic, and environmental awareness. The objective of the following paper [39] by Yang J. et al. is to investigate the characteristics of contradiction in idea creation, and use them to create better design alternatives in construction VE. An Idea Breakdown Structure (IBS) was applied as the principle of problem solving. Ding Z. et al. developed in [40] a "TRIZ and patent laboratory" (TP Lab) platform to promote innovations and manage the knowledge in the construction industry where TRIZ was applied in order to extract available patent knowledge.

7. Conclusion

Despite the fact that innovation is not the key feature of construction industry, it cannot be considered to be a technologically lagging behind. The key players on the market are cautious about innovation possibly because reliability, stability and meeting existing codes requirements are more demanded aspects. However, real breakthroughs and proven ideas could destroy that conservatism barrier.

The literature review on the subject of TRIZ application in building industry has shown that a number of researchers are working in this direction and making attempts to use TRIZ tools when it is required to find unique ideas and solve specific complex issues in such areas as development of construction techniques and technologies, design of new structures and construction materials, construction project management and value engineering, etc. However, successful application of these tools is not possible without creative adaptation. On the other hand, the number of publications in this field is relatively small which allows us to conclude that TRIZ use is still very limited in construction.

The classic Theory of Inventive Problem Solving was created to solve common technical issues and, therefore, does not provide specific tools for specific industries. Despite that TRIZ has proven to be a quite unique methodology, there are still many controversial situations requiring TRIZ tools to be adapted to a specific industrial field, and construction is not an exception. For practical use of TRIZ in technic it is necessary to have a number of specialized versions of TRIZ differing by nomenclature and content of information assets. The same target can be set regarding construction industry.

8. Suggestion for future work

The review result has shown that the most applied TRIZ tool in construction is the Contradiction Matrix that presents a database of known solutions and enables stakeholders to resolve contradictions using 40 inventive principles. Based on above, it is relevant to adapt such TRIZ tool as the contradiction matrix to problem solving in construction

engineering and management and provide a number of case studies. In this case such methodology could be brought into conservative industries like construction more easily. Supporting this idea, we can add that similar studies were already performed in papers [41]–[45] for such areas as Process Engineering, Redesign Service, Quality Improvement, Electric Energy Storage Systems and Service Related Context.

Acknowledgements

The authors would like to acknowledge TEKES, the Finnish Funding Agency for Innovation and its program FiDiPro for the support.

Also thanks to Iuliia Shnai (Research Assistant at LUT, School of Industrial Engineering and Management) for her help in literature search.

References

- [1] "Chinese construction firm erects 57-storey skyscraper in 19 days," *The Guardian*, 2015. [Online]. Available: <http://www.theguardian.com/world/2015/apr/30/chinese-construction-firm-erects-57-storey-skyscraper-in-19-days>. [Accessed: 08-May-2015].
- [2] U. Kulatunga, R. Amarantunga, and R. Haigh, "Construction innovation: a literature review on current research," pp. 654–662, 2006.
- [3] Y. Salamatov, *TRIZ: the right solution at the right time: a guide to innovative problem solving*, 2nd ed. 2005.
- [4] G. S. Altshuller, L. Shulyak, and S. Rodman, *40 Principles: TRIZ Keys to Technical Innovation*. Technical Innovation Center, INC., 1997.
- [5] U. N. K. Vignesh, "Introduction to TRIZ concept," in *Proceedings of the National Conference on Emerging Trends In Mechanical Engineering 2k13*, 2013, pp. 203–207.
- [6] D. Cavallucci, "World Wide status of TRIZ perceptions and uses a survey of results," 2009.
- [7] A. R. Rumane, *Quality Management in Construction Projects*. Boca Raton, FL: Taylor & Francis Group, 2010.
- [8] J. Dale, "Innovation in construction : ideas are the currency of the future," *The Chartered Institute of Building*, Berkshire, 2007.
- [9] A. M. Blayse and K. Manley, "Key influences on construction innovation," *Construction Innovation: Information, Process, Management*, vol. 4, no. 3, pp. 143–154, 2004.
- [10] W. J. Ding Z., Jiang S., "Research on Construction Technology Innovation Platform Based on TRIZ," 2013, pp. 211–223.
- [11] S. Asad, M. M. A. Khalfan, and P. McDermott, "Promoting Innovative thinking within Construction," pp. 62–71.
- [12] B. Ozorhon, C. Abbott, G. Aouad, J. Powell, and U. of S. Design and Print Group, "Innovation in Construction: A Project Life Cycle Approach," *SCRI Res. Rep.* 4, no. May, 2010.
- [13] T. M. Toole, "Technological Trajectories of Construction Innovation," *J. Archit. Eng.*, vol. 7, no. 4, pp. 107–114, 2001.
- [14] Z. Ding and J. Ma, "An exploration study of construction innovation principles: Comparative analysis of construction scaffold and template patents," in *Proceedings of the 17th International Symposium on Advancement of Construction Management and Real Estate*, 2014, pp. 843–850.
- [15] D. M. Conall Ó Catháin, "Construction innovation using TRIZ," in *Global Innovation in Construction Conference 2009*, 2009, no. Loughborough University, Civil and Building Engineering, pp. 296–306.
- [16] Y. Mohamed, "A Framework for systematic improvement of construction systems," University of Alberta, 2002.
- [17] S. Mohamed, Y., AbouRizk, "Triz for structuring construction innovation," in *Canadian Society for Civil Engineering - 31st Annual Conference: 2003 Building our Civilization*, 2003, pp. 241–249.
- [18] Y. Mohamed and S. AbouRizk, "Application of the Theory of Inventive Problem Solving in Tunnel Construction," *J. Constr. Eng. Manag.*, vol. 131, no. 10, pp. 1099–1108, 2005.
- [19] R. C. Shao-tsai Cheng, Wen-der Yu, Chih-ming Wu, "Analysis of construction inventive patents based on TRIZ," in *Proceedings of the International Symposium on Automation and Robotics in Construction and Mining*, 2009, pp. 1–6.
- [20] W.-D. Yu, C.-M. Wu, and W.-C. Lien, "Fast innovation of construction technologies with computer aided innovation tools," in *The 25th International Symposium on Automation and Robotics in Construction. ISARC-2008*, 2008, pp. 521–527.
- [21] H. T.-W. Yu W.-D., Wu C.-M., "Development and application of a systematic innovation procedure for construction technology," in *2009 26th International Symposium on Automation and Robotics in Construction. ISARC*, 2009, pp. 149–159.
- [22] C.-M. . Wu, W.-D. . Yu, and S.-T. . Cheng, "A model used for the generation of innovative construction alternatives," .
- [23] Kevser Coşkuna; M. Cem Altun, "A Conceptual Model for Improving In-Situ Construction Techniques Using Triz and Six Sigma Approaches," in *Research, Development, and Practice in Structural Engineering and Construction*, 2013.
- [24] K. C. M. C. Altun, "Applicability of TRIZ to In-Situ Construction Techniques," in *International Proceedings of Economics Development & Research*, 2011, p. 17.
- [25] P. C. Lin, Y.H. Lee, "Applying TRIZ to the construction industry," in *10th International Conference on Civil, Structural and Environmental Engineering Computing, Civil-Comp 2005*, 2005, p. 12.
- [26] Y. Luo, Y. Shao, and T. Chen, "Study of New Wall Materials Design Based on TRIZ Integrated Innovation Method," *Manag. Sci. Eng.*, vol. 6, no. 4, pp. 15–29, 2012.
- [27] D. J. Chen, Z., Li, H., Chung, J.K.H., Shen, G.Q.P., Clements-Croome, "A triz based value management process for selecting façade solutions," in *Inaugural Asia Pacific Value Convention 2006: The World of Innovation - Incorporating the 8th HKIVM International Conference and the 11th Biennial Conference of IVMA*, 2006, pp. 288–295.
- [28] R. Sen Chiu and S. T. Cheng, "The improvement of heat insulation for roof steel plates by triz application," *J. Mar. Sci. Technol.*, vol. 20, no. 2, pp. 122–131, 2012.
- [29] D. Lee and S. Shin, "Advanced high strength steel tube diagrid using TRIZ and nonlinear pushover analysis," *J. Constr. Steel Res.*, vol. 96, pp. 151–158, 2014.
- [30] TRIZ Research Team, "DSDI TRIZ," POSCO online news., 2009. [Online]. Available: <http://www.posco.co.kr/homepage/docs/kor/jsp/news/posco/s91fnews002p.jsp?idx=186751;2009>. [Accessed: 20-Apr-2015].
- [31] S. S. Lee D., "High tensile UL700 frame module with adjustable control of length and angle," *J. Constr. Steel Res.*, vol. 106, pp. 246–257, 2015.
- [32] S. Craig, D. Harrison, A. Cripps, and D. Knott, "BioTRIZ Suggests Radiative Cooling of Buildings Can Be Done Passively by Changing the Structure of Roof Insulation to Let Longwave Infrared Pass," *J. Bionic Eng.*, vol. 5, no. 1, pp. 55–66, 2008.
- [33] B. R. Cabrera and G. J. Li, "A lean-TRIZ approach for improving the performance of construction projects," in *Proceedings IGLC-22*, June 2014 | Oslo, Norway, 2014.
- [34] H. Cui, "Exploring Conflict Resolution Methods for Construction Projects: A TRIZ Theory Perspective," in *ICCREM 2014*, 2014, pp. 791–796.
- [35] S.-M. Chang, P.-L., Yu, W.-D., Cheng, S.-T., Lee, "Exploring underlying patterns of emergent problem-solving in construction with triz," in *27th International Symposium on Automation and Robotics in Construction, ISARC 2010*, 2010, pp. 607–616.
- [36] S.-M. Chang, P.-L., Yu, W.-D.c, Lee, "A General Construction Problem-Solving Model based on lessons-learned approach," *J. Chinese Inst. Civ. Hydraul. Eng.*, vol. 24, no. 4, pp. 415–428, 2012.
- [37] X. Zhang, X. Mao, and S. M. AbouRizk, "Developing a knowledge management system for improved value engineering practices in the construction industry," *Autom. Constr.*, vol. 18, no. 6, pp. 777–789, 2009.
- [38] X. Mao, X. Zhang, and S. M. AbouRizk, "Enhancing Value Engineering Process by Incorporating Inventive Problem-Solving Techniques,"

- Journal of Construction Engineering and Management, vol. 135, no. 5, pp. 416–424, 2009.
- [39] J. Yang, H. Baeg, and S. Moon, "Utilization of contradiction for creating design alternatives in construction value engineering," *KSCE Journal of Civil Engineering*, vol. 18, no. 2, pp. 355–364, 2014.
- [40] F. Ding, Z. Wang, J. Ng, "Innovation and patent knowledge management in the construction industry," in *17th International Symposium on Advancement of Construction Management and Real Estate, CRIOCM 2012*, 2012, pp. 833–842.
- [41] C. Pokhrel, "Adaptation of TRIZ Method for Problem Solving in Process Engineering," Lappeenranta University of Technology, 2013.
- [42] N. Gazem and A. A. Rahman, "Improving TRIZ 40 Inventive Principles Grouping in Redesign Service Approaches," *Asian Soc. Sci.*, vol. 10, no. 17, pp. 127–138, 2014.
- [43] C.-L. Yang, "Using Modified TRIZ Approach for Quality Improvement," *Sci. J. Bus. Manag.*, vol. 1, no. 1, p. 14, 2013.
- [44] A. Albers, D. Wagner, L. Kern, and T. Höfler, "Adaption of the TRIZ Method to the Development of Electric Energy Storage Systems," *Procedia CIRP*, vol. 21, pp. 509–514, 2014.
- [45] N. Gazem and A. A. Rahman, "Interpretation of TRIZ Principles in a Service Related Context," *Asian Soc. Sci.*, vol. 10, no. 13, pp. 108–130, 2014.

Publication II

Renev I.

**Computer-aided conceptual design of building systems.
Linking design software and ideas generation techniques**

Reprinted with permission from
Advances in Systematic Creativity
Creating and Managing Innovations

Ed. 1, Chapter 13, pp. 201-224, 2019

© 2019, Palgrave Macmillan
(not to be published online until the end
of a 24-month embargo period)

Publication III

Renev I., Chechurin L., Perlova E.

**Early design stage automation in Architecture-Engineering-Construction (AEC)
projects**

Reprinted with permission from
Proceedings of the 35th eCAADe Conference

Vol. 1, pp. 373-382, 2017

© 2017, eCAADe (Education and Research in Computer Aided Architectural Design in Europe) and Dep. of Civil, Building and Environmental Engineering, Faculty of Civil and Industrial Engineering, Sapienza University of Rome.

Early design stage automation in Architecture-Engineering-Construction (AEC) projects

Ivan Renev¹, Leonid Chechurin², Elena Perlova³

^{1,2}Lappeenranta University of Technology (LUT) ³Saint-Petersburg State Polytechnical University

¹ivan.renev@student.lut.fi ²leonid.chechurin@lut.fi ³elena.perlova12@gmail.com

The paper is dedicated to conceptual design stage in AEC projects since this stage defines most of further design and even construction. Conceptual design is less automated and more human depended part of a complex design process. It is reasonable to link modern construction design software with ideas generation techniques in order to enhance and automate design creativity and effectiveness. In the article we propose computer-aided automation of searching for new conceptual ideas and nontrivial solutions during early design stage in AEC projects using such TRIZ tools as Function Modelling and Trimming in BIM technology. For description of our approach we consider framed buildings.

Keywords: TRIZ, BIM, AEC, Function analysis, Trimming

INTRODUCTION

Early design stage in Architecture and Construction projects is a crucial part of sophisticated long-term design process. This stage is also known as Conceptual Design (CD) and here many fundamental and critical solutions are taken. The more smart and nontrivial solutions are taken during CD, the more technological, effective and less costly design we gain. Those solutions can be found by using different techniques of ideas generation, such as a morphological chart, synectics, brainstorming, TRIZ tools, etc. TRIZ is believed to be one of the most effective and well-structured problem-solving techniques (Altshuller 1999), (Salamatov 2005) and it is well applicable to architecture and construction (Conall Ó Catháin 2009), (Lin and Lee 2005), (Mohamed and AbouRizk 2003). "TRIZ" is the Russian acronym for the "Theory of Inventive Problem Solving." G.S. Alt-

shuller and his colleagues developed the method between 1946 and 1985. The approach includes a number of tools, some of the most used are the Ideal Final Result and Ideality; Functional Modeling, Analysis and Trimming; the 40 Inventive Principles of Problem Solving. In our digital century it is reasonable to link modern construction design software with ideas generation techniques in order to enhance and automate design creativity. Nowadays Building Information Modelling (BIM) became popular stream in construction design. Existing BIM software have range of instruments enabling designers to bring all their knowledge and experience into projects but, however, those software do not support users in searching for nontrivial conceptual ideas for design. That is why the ideas generation stage is still a separate, not automated and human depended part of design. In the article we propose computer-aided automation

of searching for new conceptual ideas and nontrivial solutions during early design stage in AEC projects using TRIZ tools in BIM technology. For description of our approach we will consider framed buildings.

STATE OF THE ART

Linking engineering design software with ideas generation techniques and development of CAI (Computer-Aided-Invention) systems is still a researchable topic. (Ikovenko 2004) mentioned that merging TRIZ with other methods gave birth to several integrated methodologies based on TRIZ and it opened new horizons for CAI development to cover all the parts of those methods, both analytical and concept generating. Also (Bakker et al. 2011) explained the link that is missing between CAI and CAD (Computer-Aided Design) software. Furthermore, they proposed the integration of CAI and CAD software. Also (Noel 2001) suggested integrating TRIZ and CAD in order to increase design effectiveness and productivity. Also the review of existing literature in the field of architecture and construction showed that new technological advancements in AEC design has brought the "level of automation" as a pivotal factor in the success of projects. (Abrishami et al. 2013) show that extant literature has identified a significant knowledge gap concerning the key impact links and support mechanisms needed to overtly exploit computational design methods, especially BIM, throughout the conceptual design stage. Moreover, most of the respondents studied in the paper highlighted several deficiencies in the existing tools, whilst they asserted that such a purposeful BIM interface can offer comprehensive support for automation of the entire of AEC design and implementation phases, and particularly enhance the decision making process at the early design phases.

DESCRIPTION OF THE APPROACH

According to [1] Autodesk Revit® was determined as a leader among the best BIM software products by customer satisfaction (based on user reviews) and scale (based on market share, vendor size, and so-

cial impact). Autodesk Revit is BIM software for architects, structural engineers, MEP engineers, designers and contractors. It allows users to design a building and structure and its components in 3D, annotate the model with 2D drafting elements, and access building information from the building model's database. Based on above, Autodesk Revit® was selected by the authors as the basic and most promising software for realization of a proposal for conceptual design stage automation in AEC projects. Moreover, this is the only software that has a built-in open source graphical programming tool for design which extends building information modeling with the data and logic environment of a graphical algorithm editor and enables users to significantly expand functionality of the software without having special knowledge of programming. The tool is called Dynamo. In our approach software is supposed to self-analyze Building Information Model and suggest solutions in order to improve the system. For that purpose we suggest to use the TRIZ Functional Modeling and rules of trimming. In order to teach software to extract a function model from BIM model we have built a special script with help of Dynamo. The script first automatically detects elements/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. On the next step 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 also applies special 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 on elements and functions. Also, the software helps to achieve a more complete and convenient workflow

for design engineers as all is done within the BIM environment. Finally, having this overview is a prerequisite for performing 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 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 design engineer can accept or decline those proposals. In function ranking functions of elements are ranked on their level of usefulness. In order to perform ranking we first have to identify a "target function" (for instance, "carry live load"). The higher 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 co-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 nontrivial design avoiding complex processes of topology optimization and structural analysis which are issues for further detailed design. As a case study we analyze a simple beam structural system.

Figure 1
the circuit scheme

FUNCTION ANALYSIS OF A BIM MODEL

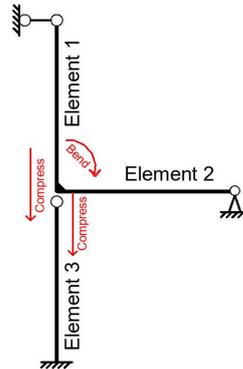
Interaction matrix

Building the interaction matrix is the first step in the functional analysis. Here the position of elements in space, their geometric characteristics and functions

are not taken into account. The matrix of interactions represents the model as a system of individual elements interacting with each other in order to perform the functions assigned to them. Identifying the presence of interaction between the elements of the system is the goal of this type of analysis. The aim of this part of the study is to automatically construct the interaction matrix based on the result of the BIM model analysis. In order to do this, the following tasks must be performed:

1. Analyze the BIM model for the presence of physical interaction between its components;
2. Output the result as the final interaction matrix in a user-friendly way.

Algorithm for conducting analysis to identify interactions between elements. As an illustrative example, we consider the following system, shown in Figure 1, consisting of three elements. The circuit can be represented as a sequential list of elements.



Further, each element of the list is sequentially examined with respect to the list of elements. Elements are (i) intersected, (ii) not intersected or (iii) self-intersected. Self-intersections of elements are excluded.

Based on the data obtained from the analysis of the interaction of elements, a matrix is constructed.

	Element 1	Element 2	Element 3
Element 1	✓	✓	✓
Element 2	✓	✓	✓
Element 3	✓	✓	✓

	Element 1	Element 2	Element 3
Element 1	C	-	C
Element 2	B	C	C
Element 3	-	-	B

Output of the analysis result. The table is automatically formed in an Excel file, which is generated after the script is run based on the analysis result of the BIM model elements. The output of the result in a text form is the most clear and understandable way.

Defining functions of elements

The second step in the functional analysis is the construction of a matrix of functions of elements. When constructing the interaction matrix, we did not take into account the geometric characteristics of the elements, their position in space. The goal of constructing the interaction matrix was to reveal the fact of the physical interaction of the elements. The next step in the analysis is definition of the functions of the interacting elements relative to each other. Thus, we gradually go deeper into the analysis of the model, moving from the general to the particular.

Algorithm of actions in determining the functions of elements. Based on the data obtained during the construction of the interaction matrix we can judge the number of interactions in the model.

Let us return to our simplified model and consider the functions of the elements. Let us assume that the live load in our system acts along the Z axis and no other loads are applied to the model. Figure

1 shows that Element 1 compresses Element 3, and Element 2 bends Element 1 and compresses Element 3.

Further, for clarity of the results of the two previous analyzes, we represent the function table in the form of a matrix of functions. The elements are located vertically and horizontally, and their functions at the intersection. The following notations are used for the functions:

1. Compress - C;
2. Bend - B;
3. Stretch - S;
4. Torque - T;

Defining functions by category of elements. The purpose of defining the functions of the elements is to prepare the data for ranking the BIM model elements. Therefore, in this study, it was decided to take into account the functions of elements that require special attention: compression, bending, torsion.

The Table 1 shows the functions that correspond to the interactions of elements of different categories. The categories were chosen according to the principle of the most common in framed systems.

Category 1	Category 2	Hinged connected	Function
Foundation	Column	+	C
Foundation	Column	-	C + B
Column	Column	+	C
Column	Column	-	C + B
Column	Beam	+	C
Column	Beam	-	C + B
Beam	Slab	+	C
Beam	Slab	-	C + B
Beam	Beam	+	B
Beam	Beam	-	B + T

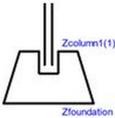
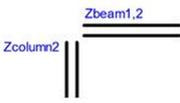
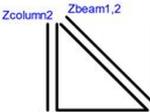
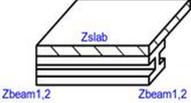
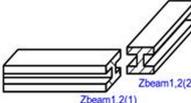
In order to determine the functions of the elements programmatically, it is also required to specify the position in space, namely the coordinates of the elements in the BIM model. It is important to specify the coordinates of the bottom and top for the linear objects: beams, columns. And the lower level for the objects elements: foundations. A floor slab is also accepted as an object element, since the lower level at each point of the plate will be the same.

Figure 2
The matrix of interaction

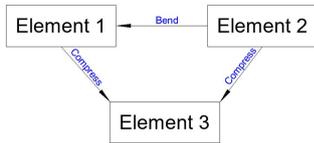
Figure 3
The matrix of functions

Table 1
Functions of elements

Table 2
Conditions of
positioning of
elements

Category 1	Category 2	Condition	Scheme of interaction	Description
Foundation	Column	$Z_{foundation} < Z_{column1}$		Column influences on foundation. Column has function.
Column (1)	Column (2)	$Z_{column1(1)} < Z_{column1(2)}$		Column (2) influences on Column (1). Column (2) has function.
Column	Beam	1) If $Z_{beam1} = Z_{beam2}$:		Beam influences on column. Beam has function.
		1.1) $Z_{column2} = Z_{beam1,2}$		
		1.2) $Z_{column1} = Z_{beam1(2)}$ (only for rigid connection)		
		2) If not $Z_{beam1} = Z_{beam2}$:		
		2.1) $Z_{column2} = Z_{beam1(2)}$		
Beam	Slab	$Z_{beam1}(Z_{beam2}) < Z_{slab}$		Slab influences on beam. Slab has function.
Beam (1)	Beam (2)	$Z_{beam1,2(1,2)} = Z_{beam1,2(1,2)}$ and $X_{beam1(1)} < X_{beam2(1)} < X_{beam1(2)}$		Beam (2) influences on beam (1). Beam (2) has function.

The functions of interest are appeared when conditions described in the Table 2 are met:



Information output. It is supposed to carry out the output of information by analogy with the matrix of interactions. After the script is run, the result is generated in the created Excel file.

Function diagram

The construction of a function diagram is the third step in the functional analysis. The functional diagram displays the 3D model in 2-dimensional form, where each element is presented in the form of a block with the name of the element. Let us call it "block of the element". The interaction between them is displayed in the form of an arrow. Hereinafter - "arrow of interaction". The presence of an arrow between the blocks will indicate the presence of interaction between the elements and the direction of the arrow indicates the direction of the action. The nature of the interaction (functions), as a rule, is written above the arrows. Construction of the functional diagram is especially important for the analysis of complex systems with a large number of elements and functions.

Construction of the functional diagram is convenient for monitoring of unwanted functions and the state of the model after trimming when the function analysis is repeated. Let us construct a functional diagram for the model, which was considered earlier. This diagram is shown on Fig. 4.

The elements of the considered model are located in the same plane, so the construction of the functional diagram does not cause difficulties, however, when it comes to circuits which elements are placed in three planes OX, OY and OZ, it becomes

necessary to adopt new rules due to the need to transform the usual three-dimensional space into a two-dimensional space.

Function diagram generation. Common principles. In order to continue this study, we develop a two-dimensional model into a three-dimensional one. To do this, we add several elements in the direction of the axis OY (see Figure 5).

Figure 4
Functional model diagram

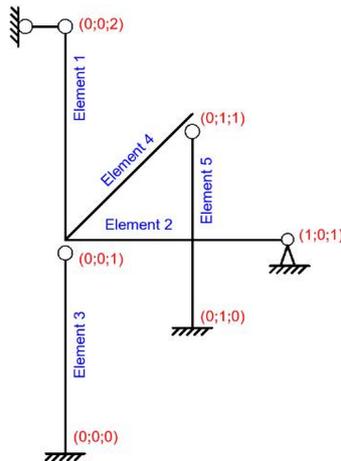


Figure 5
3D framed scheme

To place elements in the form of blocks in a functional diagram we need to group all the elements of the model according to a common principle. For this principle the Z coordinate of the lowest point of each element was chosen.

For the following categories of elements, most commonly encountered in framed building systems, the following levels are used in the analysis:

- Column - Zcolumn1;
- Foundation - Zfoundation;
- Floor slab - Zslab;
- Beam - Zbeam1 or Zbeam2 (Choose a lower value)

Figure 6
Placement of
elements in a
function model

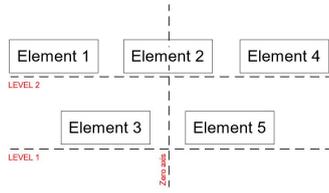


Figure 7
Matrix of functions

Exposed element	Element 1	Element 2	Element 3	Element 4	Element 5
	Element 1	Element 2	Element 3	Element 4	Element 5
Element 1	-	-	C	-	-
Element 2	B	-	C	-	-
Element 3	-	-	-	-	-
Element 4	B	-	C	-	C
Element 5	-	-	-	-	-

Table 3
Position of
elements

1. Let us take the length of each element of the model shown in Figure 5 is equal to 1m. The coordinates of the lower points of the elements are also shown in Figure 5;
2. Let us compose the table on the basis of the data from the model, in the first column of which the names of the elements are indicated and in the second one coordinate Z of the lower level of the element;
3. Let us group the contents of the table into levels equal to the Z coordinate, as shown in Table 3.
4. Let us place the blocks of the elements in the space of the diagram according to the detected levels. Elements are placed with an equal step symmetrically to the central axis (see Figure 6).

To create the arrows of interaction in functional diagram, let us consider the matrix of functions for the studied circuit. It consists of influencing elements vertically and of exposed ones horizontally. At the intersection of the horizontal and vertical axes are the functions of the acting element. It is necessary to read the matrix of functions from left to right, as indicated in Figure 7. Element 1 compresses Element 3. Thus, the arrow of interaction for interaction Element 1 - Element 3 will look as shown in Figure 8.

Function diagram generation. Dynamo realization. Implementation of this step by software is carried out by analyzing the elements of the BIM model.

1. The program extracts the coordinates of the bottom level of each individual element;
2. Based on the extracted data, the list of elements is divided into several sub-lists, all elements of the same list have a common Z coordinate. Each sub-list corresponds to a separate level in the functional diagram;
3. Next, a block family is created that is placed on the drawing view in Revit with an equal step along X in an amount equal to the number of elements in each separate sub-list and with an equal step along Y in an amount equal to the number of sub-lists;

Level in FD	Element's name	Z coordinate(m)
Level 1	Element 3	0
	Element 5	
	Element 1	
Level 2	Element 2	1
	Element 4	
	Element 4	

4. The element name is written to the block parameter.

Thus, the functional diagram for the circuit will look like on the Figure 8.

In order to create arrows of interaction in Dynamo, a matrix of functions was used. The program performs the following algorithm of actions:

1. The matrix of the model function is analyzed. A list with "Element - Function - Element" elements is created;
2. On the functional diagram elements are searched for by name according to the list obtained;
3. A family is created based on the arrow line in Revit. A parameter is added to the family to which the function will be written later,
4. An interaction arrow is created from the influencing element to the exposed one. The arrow is created as a line in two clicks from one object to another. In order to find the point of the first and second clicks, the coordinates of blocks of the influencing and exposed elements in the list are tracked;

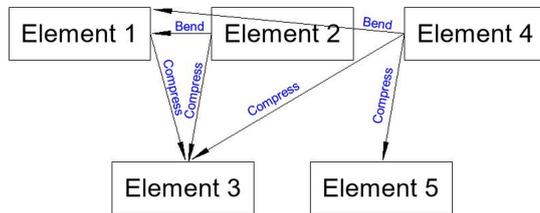


Figure 8
Function model of a
BIM model of a
framed structure

5. The function of the influencing element is written above the arrow.

Ranking

Ranking is an analysis that precedes the main objective of functional analysis - trimming. It implies a discrete examination of the elements of the model under a number of criteria according to which the elements are assigned a rank. The higher the rank of the element, the higher its significance in the model and the higher the chance of remaining in the model after the trimming.

According to different ranking methods, the criteria for evaluating the model have different scales of evaluation: alphabetic, numerical and so on. The numbers obtained as a result of the ranking for the element are summed up, the letters are added to the number and can have their significance.

Formation of the first ranking rule

Closeness to a target function. The work of the elements in the framed building system is, as a rule, reduced to one final goal. For example, the work of the beams is reduced to keeping the slab plate. In turn, these beams are supported by columns. From the above, we conclude that the work of beams and columns of the first floor is reduced to providing a stable position in the space of the first floor slab. Floor slab is needed in order to carry a live load, which includes the weight of people, equipment, etc. Thus, it can be said that the slab is the key element necessary to achieve the ultimate goal of design and operation.

We have combined all the elements into three

main groups according to the degree of closeness to a target function:

1. Elements of category "A" - high importance of elements;
2. Elements of category "B" - the average significance of the elements;
3. Elements of category "C" - low significance.

In the framed systems, the following elements have been identified, the function of which is targeted, that is, the elements cannot be trimmed:

1. Foundations
2. Floor slabs
3. Roof slab

The listed elements belong to the first group and are marked with the letter "A".

Elements of the second group are elements which work is aimed at helping to achieve a target function. These elements are marked with the letter "B". These elements also have high significance in the model. Such elements can be identified through the following criteria:

1. The element interacts with the element that performs the target function;
2. The Z coordinate of the bottom point of the element is below the coordinate of the lowest point of the element that performs the target function

Elements that do not interact with the "target elements" or have the Z coordinate higher than the Z coordinate of the target element, refer to the third group and are marked with the letter "C".

Formation of the second ranking rule

Harmful functions. An important factor in the work of a structure is the function of its individual elements. Along with target functions, there are so-called harmful functions caused by certain factors. For example, the rigid connection of two columns provokes the appearance of compression and bending forces, and the hinged one - compression. The bending force will be harmful. The presence of harmful functions will also cause a decrease in the rank of the element. The following types of functions are assigned a certain number of points:

1. Compress - (-1);
2. Bend - (-2);
3. Torque - (-3)

Table 4
The results of ranking

Element's name	Closeness to the target function	Presence of negative functions	Presence of positive functions	Overall result
Element 1	C	-1		-1C
Element 2	A	-3		-3A
Element 3	B		6	B+6
Element 4	C	-3		-3C
Element 5	C		2	C+2

Formation of the third ranking rule

Useful functions. The third rule is the opposite to the second rule and take into account only positive functions, which include:

1. Stretch - 1;
2. Hold - 2.

Figure 9
Circuit scheme after trimming

Consider the circuit shown in Figure 5, let Element 2 performs a target function in the model. We will analyse it according to the rules presented above.

1. According to 1st principle of ranking, Element 3 gets "B", because Element 2 has target function and Element 3 holds Element 2, Element 2 gets "A";
2. According to 2nd principle of ranking, Element 2 bends Element 1 and compresses Element 3, Element 4 bends Element 1 and compresses Element 3, so Elements 2, 4 gets (-3), Element 1 compresses Element 3 and gets (-1);

3. According to 3rd principle of ranking, Element 3 and Element 5 have positive functions. Element 5 holds Element 4 and Element 3 holds Element 1, 4, 2

The results of the total ranking are given in Table 4.

The rank of the elements is not the sum of the scores based on the results of evaluating the elements on three grounds. The rank of the element is represented as follows:

$$R = (-X)N(+Y) \tag{1}$$

where X is the total number of harmful functions performed by the element;
N - the letter designation of the group;
Y - the total number of positive functions performed by the element.

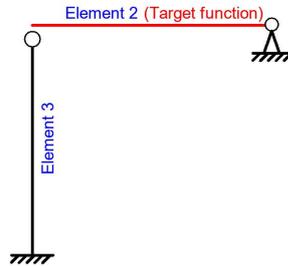
Trimming

Trimming is the main goal of functional analysis. At this stage non-functional elements are "cut off" and the useful functions of the elements are transferred to other elements of the model.

Rules of trimming:

1. Removal of elements occurs only if they fall in the category "C";
2. Elements with harmful functions are highlighted in the model

After trimming, the circuit is transformed into the following:



CONCLUSION

In this research we obtained a result that allows designers to automatically analyse and exclude non-functional elements from the model and propose a solution to prevent unfavorable functions of its elements. The key advantage is that this analysis is being done on early design stage before deep structural analysis which is time and cost consuming.

SUGGESTIONS FOR FURTHER WORK

After the function analysis has been done, we propose to analyse the trimmed model using another TRIZ tool called Contradiction analysis. This part of analysis is the final part of the conceptual design phase. Contradiction analysis includes 40 techniques to eliminate technical contradictions. A technical contradiction in TRIZ is a situation where an attempt to improve one characteristic of a technical system causes worsening of another. For more effective organization of use of techniques a special table has been developed. There are the characteristics of technical systems need to be improved and characteristics that are worsened. At the intersection of the table graphs the numbers of solutions are indicated which help to eliminate the arisen technical contradiction. For construction field the revision of all proposed technical characteristics was carried out in order to identify the methods most suitable for use in the construction area. Our goal is to implement these tools in the design process. To achieve this goal it was decided to link the possibilities of this tool with categories of the model's elements.

The software implementation of this tool should be implemented as follows:

1. Selection of the model element;
2. Selection of the worsening parameter;
3. Selection of the improving parameter;
4. Obtaining a number of solutions to the technical contradiction for the category of selected element.

Implementation of the 2nd and 3rd steps of the presented algorithm will be performed using Windows Form selection windows. Getting information about

the element, analyzing the input data and output the result of the analysis will be done using the Dynamo visual programming tool based on the Revit software.

ACKNOWLEDGEMENTS

The authors would like to acknowledge OIPEC, the Open Innovation Platform for University-Enterprise Collaboration: new product, business and human capital development (Grant Agreement No.: 2015-3083/001-001) for the support

REFERENCES

- Abrishami, S., Goulding, J. S., Rahimian, F. P. and Ganah, A. 2014, 'Integration of BIM and generative design to exploit AEC conceptual design innovation', *Journal of Information Technology in Construction*, 19, pp. 350-359
- Altshuller, G. S. 1999, *The innovation algorithm: TRIZ, systematic innovation and technical creativity*, Technical Innovation Ctr; 1st edition
- Bakker, H. M., Chechurin, L.S. and Wits, W.W. 2011 'Integrating TRIZ function modeling in CAD software', *Proceedings of TRIZfest-2011*, p. 18
- Conall Ó Catháin, D. M. 2009 'Construction innovation using TRIZ', *Global Innovation in Construction Conference 2009*, Loughborough University, Civil and Building Engineering, p. 296-306
- Ikovenko, S. 2004 'TRIZ and Computer Aided Inventing', *Building the Information Society*, pp. 475-485
- Lin, P. C. and Lee, Y.H. 2005 'Applying TRIZ to the construction industry', *10th International Conference on Civil, Structural and Environmental Engineering Computing, Civil-Comp 2005*, p. 12
- Mohamed, S. and AbouRizk, Y. 2003 'Triz for structuring construction innovation', *Canadian Society for Civil Engineering - 31st Annual Conference: 2003 Building our Civilization*, pp. 241-249
- Noel, L.-R. 2001 'A proposal to integrate TRIZ and CAD (Computer Aided TRIZ-based Design)', *TRIZCON 2001*
- Renev, I.A. and Chechurin, L.S. 2016 'Application of TRIZ in Building Industry: Study of Current Situation', *Procedia CIRP*, Berlin, pp. 209-215
- Salamatov, Y. 2005, *TRIZ: the right solution at the right time: a guide to innovative problem solving*, Institute of innvative design (IID)
- [1] <https://www.g2crowd.com/blog/building-design-and-building-information/best-building-design-bim-software/>

Publication IV

Renev I.

**Evaluation of a novel approach for automated inventive conceptual design of
building structures**

Reprinted with permission from
Journal of Civil Engineering and Architecture

Vol. 12 (2018), pp. 550-562, 2018

© 2018, David Publishing



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

Ivan Renev

School of Engineering Science, Lappeenranta University of Technology (LUT), Lappeenranta 53850, Finland

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

Corresponding author: Ivan Renev, doctoral student, research fields: building structures, conceptual design automation.

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 may 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 framework 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. Nimitawat 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 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.

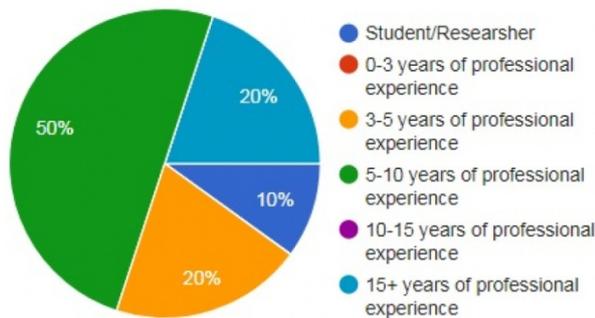


Fig. 1 Experience in the field of building structures design among the respondents.

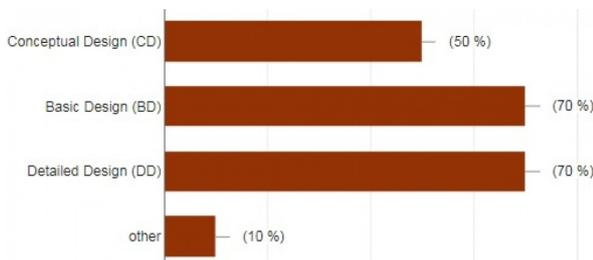


Fig. 2 Distribution of areas of activities among the respondents.

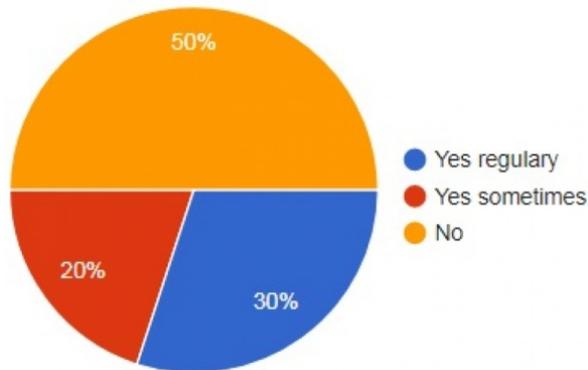


Fig. 3 Regularity of using graphical programming tools among the respondents.

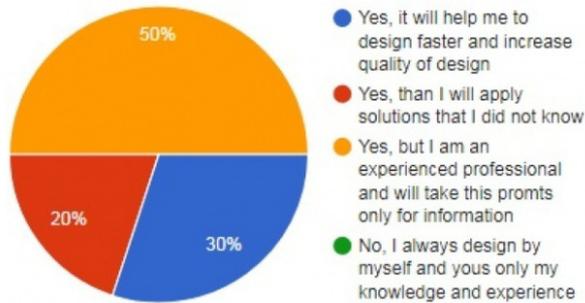


Fig. 4 The respondents' attitude regarding such a proposed software feature as giving ready prompts from a database of proven solutions.

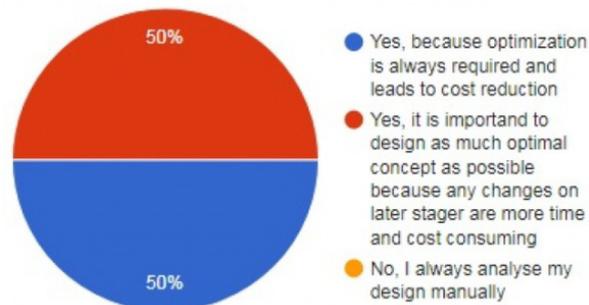


Fig. 5 The respondents' attitude regarding such a proposed software feature as automatic analysis of a conceptually designed system for functionality of its elements and suggesting optimization.

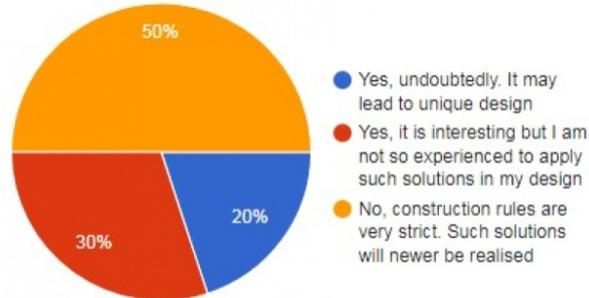


Fig. 6 The respondents' attitude regarding such a proposed software feature as giving clues for finding non-trivial solutions that are not common in construction design.

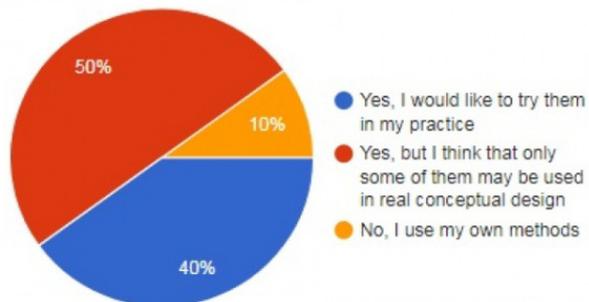


Fig. 7 The respondents' attitude to demonstrated functionality of the proposed approach.

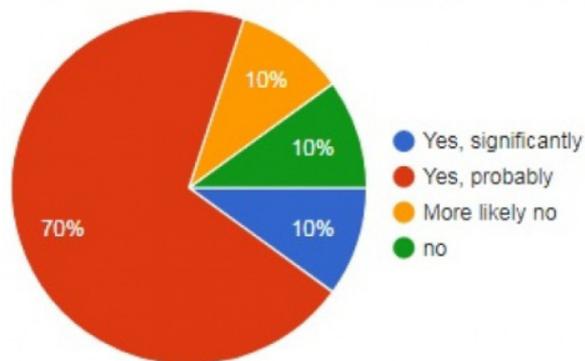


Fig. 8 The respondents' attitude regarding probability of possible improvements that may be achieved applying functionality of the proposed approach.

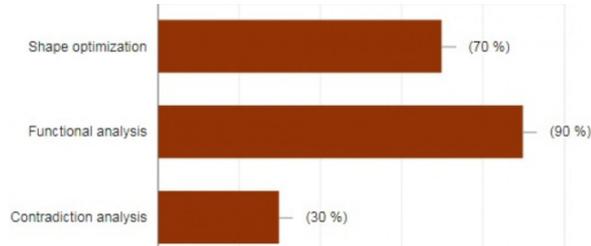


Fig. 9 The proposed approach’s functions that are found the most useful and applicable by the respondents.

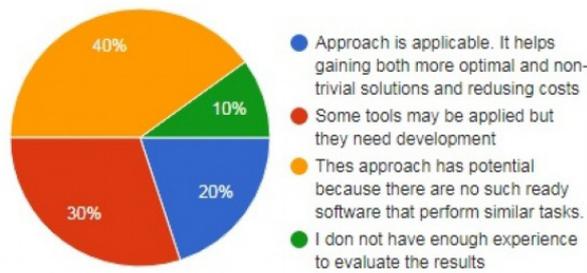


Fig. 10 Evaluation of novel approach for automated conceptual design of building structures.

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.

5.3 Survey Results Analysis

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.

Acknowledgments

The author would like to acknowledge the Finnish National Agency for Education for the positive decision on the financial support of this project (decision TM-17-10703 dated 08.02.2018).

References

- [1] Altshuller, G. S. 1999. *The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity* (1st ed.). Maryland: Technical Innovation Ctr.
- [2] Renev, I. A., and Chechurin, L. S. 2016. "Application of TRIZ in Building Industry: Study of Current Situation." *Procedia CIRP* 39: 209-15.
- [3] Renev, I., Chechurin, L., and Perlova, E. 2017. "Early Design Stage Automation in Architecture-Engineering-Construction (AEC) projects." In *Proceedings of the 35th eCAADe Conference*, 373-82.
- [4] Chechurin, L., and Collan, M., eds., 2019. "Computer-aided Conceptual Design of Building Systems. Linking Design Software and Ideas Generation Techniques." In *Advances in Systematic Creativity: Creating and Managing Innovations* (1st ed., Chapter 13), edited by Renev, I. London: Palgrave Macmillan.
- [5] Becerik-Gerber, B., and Kensek, K. 2010. "Building Information Modeling in Architecture, Engineering, and Construction: Emerging Research Directions and Trends." *Journal of Professional Issues in Engineering Education and Practice* 136 (3): 139-47.
- [6] Yalcinkaya, M., and Singh, V. 2015. "Patterns and Trends in Building Information Modeling (BIM) Research: A Latent Semantic Analysis." *Automation in Construction* 59: 68-80.
- [7] Abrishami, S., Goulding, J. S., Rahimian, F. P., and Ganah, A. 2014. "Integration of BIM and Generative Design to Exploit AEC Conceptual Design Innovation." *Journal of Information Technology in Construction* 19: 350-9.
- [8] Robertson, B. F., and Radcliffe, D. F. 2009. "Impact of CAD Tools on Creative Problem Solving in Engineering design." *CAD Computer Aided Design* 41 (3): 136-46.
- [9] Yu, W., Cheng, S., Wu, C., and Lou, H. 2012. "A Self-evolutionary Model for Automated Innovation of Construction Technologies." *Automation in Construction* 27: 78-88.
- [10] Sacks, R., Koskela, L., Dave, B. A., and Owen, R. 2010. "Interaction of Lean and Building Information Modeling in Construction." *Journal of Construction Engineering and Management* 136 (9): 968-80.
- [11] Bernal, M., Haymaker, J. R., and Eastman, C. 2015. "On the Role of Computational Support for Designers in Action." *Design Studies* 41: 163-82.
- [12] Książek, M. V., Nowak, P. O., Kivrak, S., Rosłon, J. H., and Ustinovichius, L. 2015. "Computer-aided Decision-Making in Construction Project Development." *Journal of Civil Engineering and Management* 21 (2): 248-59.
- [13] Østergård, T., Jensen, R. L., and Maagaard, S. E. 2017. "Early Building Design: Informed Decision-Making by Exploring Multidimensional Design Space Using Sensitivity Analysis." *Energy and Buildings* 142: 8-22.
- [14] Petersen, S., and Svendsen, S. 2010. "Method and Simulation Program Informed Decisions in the Early

- Stages of Building Design.” *Energy and Buildings* 42 (7): 1113-9.
- [15] Nembrini, J., Samberger, S., and Labelle, G. 2014. “Parametric Scripting for Early Design Performance Simulation.” *Energy and Buildings* 68 (PART C): 786-98.
- [16] Negendahl, K. 2015. “Building Performance Simulation in the Early Design Stage: An Introduction to Integrated Dynamic Models.” *Automation in Construction* 54: 39-53.
- [17] Paul, N., and Borrmann, A. 2009. “Geometrical and Topological Approaches in Building Information Modelling.” *Electronic Journal of Information Technology in Construction* 14: 705-23.
- [18] Brown, N. C., and Mueller, C. T. 2016. “Design for structural and energy performance of long span buildings using geometric multi-objective optimization.” *Energy and Buildings* 127: 748-61.
- [19] Fenton, M., McNally, C., Byrne, J., Hemberg, E., McDermott, J., and O’Neill, M. 2014. “Automatic Innovative Truss Design Using Grammatical Evolution.” *Automation in Construction* 39: 59-69.
- [20] Laefer, D. F., and Truong-Hong, L. 2017. “Toward Automatic Generation of 3D Steel Structures for Building Information Modelling.” *Automation in Construction* 74: 66-77.
- [21] Afzali, S. H., Darabi, A., and Niazkar, M. 2016. “Steel Frame Optimal Design Using MHBMO Algorithm.” *International Journal of Steel Structures* 16 (2): 455-65.
- [22] Song, S., Yang, J., and Kim, N. 2012. “Development of a BIM-based Structural Framework Optimization and Simulation System for Building Construction.” *Computers in Industry* 63 (9): 895-912.
- [23] Tuhus-Dubrow, D., and Krarti, M. 2010. “Genetic-Algorithm Based Approach to Optimize Building Envelope Design for Residential Buildings.” *Building and Environment* 45 (7): 1574-81.
- [24] Nimitawat, A., and Nanakorn, P. 2009. “Automated Layout Design of Beam-Slab Floors Using a Genetic Algorithm.” *Computers and Structures* 87 (21-22): 1308-30.
- [25] Kwon, D. Y., Gross, M. D., and Yi-Luen Do, E. 2009. “ArchiDNA: An Interactive System for Creating 2D and 3D Conceptual Drawings in Architectural Design.” *CAD Computer Aided Design* 41 (3): 159-72.
- [26] Shaughnessy, J. J., Zechmeister, E. B., and Zechmeister, J. S. 1947. *Research Methods in Psychology* (9th ed.). New York: McGraw-Hill.
- [27] European TRIZ Association ETRIA. 2009. “World Wide Status of TRIZ Perceptions and Uses.” [Online] Timisoara. Accessed 5 Jul. 2018. http://etria.eu/documents/TRIZ_survey_V2.pdf.

ACTA UNIVERSITATIS LAPPEENRANTAENSIS

812. SKRIKO, TUOMAS. Dependence of manufacturing parameters on the performance quality of welded joints made of direct quenched ultra-high-strength steel. 2018. Diss.
813. KARTTUNEN, ELINA. Management of technological resource dependencies in interorganizational networks. 2018. Diss.
814. CHILD, MICHAEL. Transition towards long-term sustainability of the Finnish energy system. 2018. Diss.
815. NUTAKOR, CHARLES. An experimental and theoretical investigation of power losses in planetary gearboxes. 2018. Diss.
816. KONSTI-LAAKSO, SUVI. Co-creation, brokering and innovation networks: A model for innovating with users. 2018. Diss.
817. HURSKAINEN, VESA-VILLE. Dynamic analysis of flexible multibody systems using finite elements based on the absolute nodal coordinate formulation. 2018. Diss.
818. VASILYEV, FEDOR. Model-based design and optimisation of hydrometallurgical liquid-liquid extraction processes. 2018. Diss.
819. DEMESA, ABAYNEH. Towards sustainable production of value-added chemicals and materials from lignocellulosic biomass: carboxylic acids and cellulose nanocrystals. 2018. Diss.
820. SIKANEN, EERIK. Dynamic analysis of rotating systems including contact and thermal-induced effects. 2018. Diss.
821. LIND, LOTTA. Identifying working capital models in value chains: Towards a generic framework. 2018. Diss.
822. IMMONEN, KIRSI. Ligno-cellulose fibre poly(lactic acid) interfaces in biocomposites. 2018. Diss.
823. YLÄ-KUJALA, ANTTI. Inter-organizational mediums: current state and underlying potential. 2018. Diss.
824. ZAFARI, SAHAR. Segmentation of partially overlapping convex objects in silhouette images. 2018. Diss.
825. MÄLKKI, HELENA. Identifying needs and ways to integrate sustainability into energy degree programmes. 2018. Diss.
826. JUNTUNEN, RAIMO. LCL filter designs for parallel-connected grid inverters. 2018. Diss.
827. RANAELI, SAMIRA. Quantitative approaches for detecting emerging technologies. 2018. Diss.
828. METSO, LASSE. Information-based industrial maintenance - an ecosystem perspective. 2018. Diss.
829. SAREN, ANDREY. Twin boundary dynamics in magnetic shape memory alloy Ni-Mn-Ga five-layered modulated martensite. 2018. Diss.

830. BELONOGOVA, NADEZDA. Active residential customer in a flexible energy system - a methodology to determine the customer behaviour in a multi-objective environment. 2018. Diss.
831. KALLIOLA, SIMO. Modified chitosan nanoparticles at liquid-liquid interface for applications in oil-spill treatment. 2018. Diss.
832. GEYDT, PAVEL. Atomic Force Microscopy of electrical, mechanical and piezo properties of nanowires. 2018. Diss.
833. KARELL, VILLE. Essays on stock market anomalies. 2018. Diss.
834. KURONEN, TONI. Moving object analysis and trajectory processing with applications in human-computer interaction and chemical processes. 2018. Diss.
835. UNT, ANNA. Fiber laser and hybrid welding of T-joint in structural steels. 2018. Diss.
836. KHAKUREL, JAYDEN. Enhancing the adoption of quantified self-tracking wearable devices. 2018. Diss.
837. SOININEN, HANNE. Improving the environmental safety of ash from bioenergy production plants. 2018. Diss.
838. GOLMAEI, SEYEDMOHAMMAD. Novel treatment methods for green liquor dregs and enhancing circular economy in kraft pulp mills. 2018. Diss.
839. GERAMI TEHRANI, MOHAMMAD. Mechanical design guidelines of an electric vehicle powertrain. 2019. Diss.
840. MUSIIENKO, DENYS. Ni-Mn-Ga magnetic shape memory alloy for precise high-speed actuation in micro-magneto-mechanical systems. 2019. Diss.
841. BELIAEVA, TATIANA. Complementarity and contextualization of firm-level strategic orientations. 2019. Diss.
842. EFIMOV-SOINI, NIKOLAI. Ideation stage in computer-aided design. 2019. Diss.
843. BUZUKU, SHQIPE. Enhancement of decision-making in complex organizations: A systems engineering approach. 2019. Diss.
844. SHCHERBACHEVA, ANNA. Agent-based modelling for epidemiological applications. 2019. Diss.
845. YLIJOKI, OSSI. Big data - towards data-driven business. 2019. Diss.
846. KOISTINEN, KATARIINA. Actors in sustainability transitions. 2019. Diss.
847. GRADOV, DMITRY. Experimentally validated numerical modelling of reacting multiphase flows in stirred tank reactors. 2019. Diss.
848. ALMPANOPOULOU, ARGYRO. Knowledge ecosystem formation: an institutional and organisational perspective. 2019. Diss.
849. AMELI, ALIREZA. Supercritical CO2 numerical modelling and turbomachinery design. 2019. Diss.



ISBN 978-952-335-364-0
ISBN 978-952-335-365-7 (PDF)
ISSN-L 1456-4491
ISSN 1456-4491
Lappeenranta 2019