LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT

Nikolai Efimov-Soini

IDEATION STAGE IN COMPUTER-AIDED DESIGN

ACTA UNIVERSITATIS LAPPEENRANTAENSIS 842

LUT
University

Nikolai Efimov-Soini

IDEATION STAGE IN COMPUTER-AIDED DESIGN

Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium of the Student Union House at Lappeenranta-Lahti University of Technology LUT, Lappeenranta, Finland on the 18th of April, 2019, at noon.

Acta Universitatis
Lappeenrantaensis 842

Supervisors Professor Leonid Chechurin
LUT School of Business and Management
Lappeenranta-Lahti University of Technology LUT
Finland

Associate Professor Kalle Elfvengren
LUT School of Business and Management
Lappeenranta-Lahti University of Technology LUT
Finland

Reviewer Doctor Yuri Bogdianni
Faculty of Science and Technology
Free University of Bozen-Bolzano
Italy

Opponent Full Professor Gaetano Cascini
Department of Mechanical Engineering
Politecnico di Milano
Italy

ISBN 978-952-335-340-4
ISBN 978-952-335-341-1 (PDF)
ISSN-L 1456-4491
ISSN 1456-4491

Lappeenrannan teknillinen yliopisto
LUT Yliopistopaino 2019

Abstract

Nikolai Efimov-Soini
Ideation Stage in Computer-Aided Design
Lappeenranta 2019
47 pages
Acta Universitatis Lappeenrantaensis 842
Diss. Lappeenranta-Lahti University of Technology LUT
ISBN 978-952-335-340-4, ISBN 978-952-335-341-1 (PDF), ISSN-L 1456-4491, ISSN 1456-4491

Delivering an idea and converting it into a design concept are critical steps in engineering design. In general, the departure point of these efforts is the existing version of a product or technology, an analog, or a competitor's solution. In professional practice, prior art design is represented by a 3D CAD model. Following the ideas of the design team, the model is modified, and new versions of the design are discussed, tested and selected for further detailed development. The process of ideation is basically non-systematic and time-consuming, the results are unexpected, but their value is very high: an excellent conceptual idea can make the whole design functionally successful and dramatically reduce the cost of the product and its manufacturing. This dissertation presents an approach to automate the stage of ideation and concept development. The input for this method is a 3D CAD model of an existing design, and the outputs are new design ideas that can also be presented as CAD models.

The Theory of Inventive Problem Solving (further TRIZ) provides most of the theoretical background for the new method. TRIZ tools are combined with a basic CAD modeling framework that is then further adapted and developed. A multi-criteria decision making (MCDM) procedure is added to assist quantitative selection over the set of generated design concepts. More specifically, the method uses a CAD model or sketch of the prior art design to develop its function model, then generates some new function models for a simplified design and, finally, assists in the quantitative evaluation of new designs to select the most appropriate one. Thus, the novelty of the presented work is in the integration and development of TRIZ, CAD and MCDM tools. A new method for automated CAD model complexity reduction is also proposed.

The research results enable further development of a new type of CAD software and merge professional, rigorous geometry-based design methodology and creative design tools. Once this new CAD software becomes commercially available, its systematic ideation methods will assist even those industrial design engineers who do not have much knowledge of them. Until that time, however, more work is required in programming and adapting the new tool to electronics, construction, aero/fluid dynamics and other domains.

Keywords: TRIZ, CAD, function analysis, conceptual design, system complexity reduction

Acknowledgements

This work was carried out in the School of Business and Management at Lappeenranta-Lahti University of Technology LUT, Finland, between December 2014 and April 2019. The research presented here was supported by TEKES, the Finnish Funding Agency for Innovation, and its program FiDiPro, as well as the EU Erasmus plus program and its project Open Innovation Platform for University-Enterprise Collaboration: new product, business and human capital development (Acronym: OIPEC, Grant Agreement No.: 2015-3083/001-001).

I am deeply thankful for my supervisor – Leonid Chechurin. You open for me the beautiful world of the system engineering and you gave me so much more than you could ever imagine. I am also grateful to my second supervisor and coauthor Kalle Elfvengren.

In addition, I thank my colleagues in LUT - Mariia Kozlova, Nikita Uzhegov, Ivan Renev and Iuliia Shnai for their helpful councils.

Finally, I want to thank my wife, children, parents and close friends. This work would not have been possible without your support.

Nikolai Efimov-Soini
April 2019
Lappeenranta, Finland

Contents

Abstract

Acknowledgements

Contents

List of publications 9

Nomenclature 11

1 Introduction 13
- 1.1 Research review 13
- 1.2 Research objectives and questions 14
- 1.3 Hypotheses and evolution of the method 15

2 State of the art 17
- 2.1 Systematic invention methods 17
- 2.2 Function analysis 18
- 2.3 Trimming 19
- 2.4 CAD and systematic approach collaboration 19
- 2.5 Design assessment 20

3 Validation method 22

4 Method description 23
- 4.1 3D modeling 24
- 4.2 Function analysis 25
  - 4.2.1 Component analysis 25
  - 4.2.2 Interaction analysis 27
  - 4.2.3 Function modeling 27
- 4.3 Trimming 33
- 4.4 Design assessment 34
- 4.5 Method description summary 36

5 Results 37

6 Research limitation and discussion 39

7 Conclusion 41

References 43

Publications

List of publications

I. Efimov-Soini, N. and Chechurin, L., (2015). Method of Ranking in the Function Model. *Procedia CIRP*, vol. 39, pp. 22-26.
II. Efimov-Soini, N. and Uzhegov, N., (2017). The TRIZ-based tool for the electrical machine development. *Proceedings of a conference Progress In Electromagnetics Research Symposium - Spring (PIERS)*, pp. 1396-1403, Saint-Petersburg, Russia.
III. Efimov-Soini, N. and Chechurin, L., (2017). The Method of CAD Software and TRIZ Collaboration. *Communications in Computer and Information Science*, vol. 754, Springer, pp. 517-527.
IV. Efimov-Soini, N. and Elfvengren K. (2018). Method of system model improving using TRIZ function analysis and trimming. *Advances in systematic creativity. Creating and Managing Innovations*, Palgrave Macmillan, pp. 115-131.
V. Uzhegov, N., Efimov-Soini, N. and Pyrhonen J. (2016). Assessment of Materials for High-speed PMSMs Having a Tooth-coil Topology. *Progress In Electromagnetics Research M*, vol. 51, pp. 101-111.
VI. Luuka, P., Efimov-Soini N., Collan M. and Kozlova, M. (2017). Fuzzy MCDM-procedure for Design Evaluation: Capturing Redundant Information with an Interaction Matrix. *Journal of multiple-valued logic & soft computing*, vol. 29, pp. 469-484.

Nikolai Efimov-Soini is the principal author and researcher of papers I-IV included in this dissertation. In paper V, Dr. Nikita Uzhegov was corresponding author, and Nikolai Efimov-Soini conducted the design assessment of the presented industrial model. In paper VI, Dr. Pasi Luuka was corresponding author, and Nikolai Efimov-Soini collected the case study data and prepared the designs for peer-assessment.

Nomenclature

Latin alphabet

t_i	time of the state	s
t_w	total observation time	s
N	number of function carrier links	–
N_d	number of duplicated functions	–
t_{ni}	normalised time of the state	–
FFR	final ranking factor	–
FR	ranking factor	–

Abbreviations

2D	two dimensional
3D	three dimensional
AHP	Analytic Hierarchy Process
API	application program interface
CAD	computer-aided design
QFD	Quality Function Deployment
MCDM	Multi-Criteria Decision Making
TRIZ	Theory of Inventive Problem Solving
USIT	Unified Structured Inventive Thinking

1 Introduction

1.1 Research review

According to Ullman (Ullman, 2010), 75% of a product’s cost is defined at the conceptual stage, but if a change to the original product is made later at the manufacturing stage, the cost grows exponentially. This emphasizes the importance of the early stages in a product’s lifecycle. Hence, implementing systematic methods at these stages is very useful for the design development and can minimize losses in the production process.

Furthemore, CAD software supports these early stages very well, although at the construction stage the support is rather general. CAD software, such as SolidWorks, Inventor, Kompas, SolidEdge, etc., is special engineering software used for sketching in 2D and presenting in 3D. Thus, CAD software and systematic development methods work together to achieve new design patterns, improve the development process and collaborate effectively with design process stakeholders (Bilda and Gero, 2005). Since the author is experienced in SolidWorks, it was chosen for the research in this dissertation.

There have been several attempts to improve the development process by employing systematic design tools as, for example, Axiomatic Design (Suh, 1990), USIT (Sickafus, 1997), TRIZ (Altshuller, 1984), etc. In this work, TRIZ methodology is used for the development since its formal approach and inventive tools are easy to use and understand. In addition, this methodology is widely used both in science and industry (Luo, Shao and Chen, 2012; Di Gironimo *et al.*, 2013; Chechurin, 2016).

TRIZ, in Russian “Theoria Resheniya Izobretatelskikh Zadach,” i.e., “the Theory of Inventive Problem Solving,” is an inventive method proposed by the Soviet inventor Genrikh Altshuller in 1956 (Altshuller and Shapiro, 1956). According to his report, Altshuller studied about 40,000 patents and developed formal processes for generating new ideas and technical evolution trends.

Yet product information is very uncertain at the conceptual design stage, which means that a developer must choose some concept to satisfy the product requirement using uncertain information. The price of a good idea, however, may be very high and, so, choosing the most suitable design early on becomes critical. Some multi-criteria decision-making approaches, such as AHP (Saaty, 1980), the Comparison (Pugh) matrix (Pugh, 1991), and QFD (Yoji, 1994), exist to aid the developer during concept design. In the study presented in this dissertation, AHP and the Comparison (Pugh) matrix, the two most popular methods in Finland (Salonen and Perttula, 2005), are used.

This dissertation presents a formal development method for the conceptual design stage. This approach consists of a tool whereby TRIZ, CAD, and design assessment collaborate to produce new designs.

1.2 Research objectives and questions

This chapter briefly describes the research process and its milestones, as well as the central research questions and hypotheses. The research questions defined the main ideas in this dissertation and the research roadmap. The hypotheses are technical ideas with practical implications that the method addresses. The hypotheses and evolution of the method are presented in chapter 1.3.

The primary objective of the research was to better understand the systematic approach at the conceptual design stage. This process comprises the basis for the dissertation. To accomplish the objective, literature about the design process was reviewed. The following questions were devised to guide the research:

Research question 1: What structured approaches are used for generating ideas? What approaches improve these ideas?

A clear understanding of how ideas are generated and concepts improved was needed to start the development process. Existing modeling methods were studied and reviewed in order to identify the most productive way to proceed with a development.

Research question 2: What are the methods for assessing ideas/concepts; that is, for evaluating and selecting the best and most promising for further development? How are the assessments carried out?

A poorly chosen concept can lead to financial losses. Therefore, it is crucial to minimize risk by employing a concept assessment method. To answer these questions, methods of design assessment were reviewed.

Research question 3: How can the development tools identified in the research collaborate with CAD software? Have similar studies been carried out? The primary aim of this question was to identify ways to use CAD software at the conceptual design stage.

Another objective was to propose a mechanism that would, by using an assessment method, transform a sketch, idea, or CAD model into a new original concept. This part of the development is based on a literature review, sets of ideas and surveys. The ideas proposed in the development process were verified using actual industrial case studies. In addition, the new design development process uses tools familiar to the developer, which significantly simplifies the product development process. To reach the objective, three additional research questions were proposed:

Research question 4: How to transform existing sketches/ideas/CAD models into a TRIZ function model for further modification?

This part of the work is concerned with technical issues; in particular, the problems of importing CAD model information using special software and how to present the collected information.

Research question 5: How to modify information from sketches or CAD models to receive new design possibilities?

The answer to this question lies in model improvement. Sets of ideas and actual industrial case studies were used to study the main improvement to a unique model.

Research question 6: How to evaluate the results obtained using the presented method?

This question concerns multi-criteria decision making methods and combining them with model improvement and other ideas proposed above. The most often used methods were chosen and added to the suggested method. This question is devoted to the technical implementation of the methods chosen in research question 2.

The above research questions are addressed subsequently in the text of this dissertation and reviewed again in Results, chapter 5.

1.3 Hypotheses and evolution of the method

The method presented in this dissertation is based on previous developments concerning the implementation of TRIZ in CAD software (Bakker, Chechurin and Wits, 2011; Chechurin *et al.*, 2011; Wits, Bakker and Chechurin, 2012) and on TRIZ trimming (Ikovenko, Litvin and Lyubomirskiy, 2005; Li *et al.*, 2015). The method was evaluated by using and validating a set of hypotheses. Its evolution and the hypotheses are presented in Table 1. These hypotheses pose a technical question and were validated in the industrial case study, where 18 special assembling tools were created using the method in this dissertation. The process of validation was the following: hypothesis, a test of this hypothesis during the process of engineering development, and evaluation of the development method. These industrial tools are not presented in this manuscript because they refer to trade secrets.

Table 1 - Evolution of the method and hypotheses

Hypothesis	Article	Evolution of the method
An element with many links is difficult to trim.	Article I	A formal method for ranking functions and trimming in static systems is proposed.
An element that is closer to the target is not the most important function model element.		
Function ranking is different for static and dynamic systems.	Article III	A formal method for ranking functions and trimming in static and dynamic systems is proposed.
The process of creating a function model is similar to the process of creating mesh in finite-element evaluation.	Article II	A formal method for creating a function model by using the system’s geometric features is proposed.

The result of the conceptual design stage can be rated using formal methods.	Article V and VI	Collaboration between function analysis and peer-assessment is added.
System complexity was reduced using the trimming tool for a set of functions.	Article IV	The function interaction matrix is added.

2 State of the art

This chapter briefly reviews the main topics in this dissertation. They are CAD in conceptual design, systematic invention methods, function analysis, trimming, CAD-TRIZ collaboration, and design assessment.

At the conceptual design stage, special CAD software may be used (Bilda and Gero, 2005); however, it does not support the early product design stages as well as the later ones (Hasby and Roller, 2016). Often, only the basic structure of mechanical products is known at the conceptual design stage (Hasby and Roller, 2016). Thus, in the design phases, CAD support is based on skeletal models, primitive geometries or previous designs (Fuge *et al.*, 2012; Noon *et al.*, 2012), which are used to correlate a concept with construction constraints. There are several approaches to customizing CAD software, i.e., developing or modifying the software or application, at the conceptual design stage. This software makes it possible to improve the design by modifying it. This technique is used in space development (Kucherov *et al.*, 2014), construction (Renev, Chechurin and Perlova, 2017), etc. Also, CAD developers propose model optimization based on biomimetics (*Generative Design Software. Autodesk Within*, 2017).

At present, conceptual design in popular CAD systems is represented as a tool to present the results of idea generation (*CATIA 3D Master Conceptual Design*, 2018; *Autodesk. Introduction to Concept Modeling.*, 2018) and to sort out a set of similar designs (*SolidWorks Conceptual Design*, 2018). Thus, the improvement process is only quantitative and permits just small changes in the concept; for example, a change in the shape of a car body. This approach does not permit changing the structure of the design.

2.1 Systematic invention methods

Trial-and-error has been the most popular problem solving method since ancient times. It is an iterative method based on developers' experience and trials, which are used in a new development. For creativity intensification, the following methods are often implemented: brainstorming (Osborn, 1953), morphological box (Zwicky and Wilson, 1967) and others. While these approaches may indeed contribute to decreasing development time, they do not suggest a systematic approach. In contrast to such brute force methods, systematic approaches attempt to identify a solution the first time around. There are a vast number of systematic tools to choose from, including Axiomatic Design (Suh, 1990), USIT (Sickafus, 1997), and TRIZ (Altshuller and Shapiro, 1956). In this work, TRIZ methodology is applied because it is easy to understand and to apply its formalized inventive tools. Moreover, this methodology is widely used both in science and industry (Luo, Shao and Chen, 2012; Di Gironimo *et al.*, 2013; Chechurin, 2016).

2.2 Function analysis

A function analysis systematizes initial system information (sketches, CAD model, specification, etc.) and converts it to a function model. This approach replaces the physical hierarchic presentation of the system (assembly-subassembly-part) with a function presentation (function carrier-function-object), so that new, possibly more successful, design models can be generated.

There are several methods for presenting system functions, some of which are: Functional Flow Block Diagram (FFBD) (Akiyama, 1991), Functional Analysis System Technique (FAST) (Bytheway, 2007), and Integrated Computer Aided Manufacturing Definition for Function Modeling (IDEF0) (*System engineering fundamentals*, 2001). All of these methods use the function approach for system modeling. For example, FFBD is a function-oriented approach based on the sequential relationship of all system functions. The FFBD develops a system from top to bottom, providing a hierarchal view of the functions across a series of levels. Each one aims to identify a single task at a higher level using functional decomposition. The FAST diagram differs from FFBD in that it focuses on a product’s functions rather than its specific design. FAST depicts the system as a tree structure, where each function is presented in a verb + noun format. IDEF0 includes a definition of a graphical modeling language and a description of a methodology for system modeling. In the system presentation, each part, activity or manufacturing process is presented as a box with a verb-based label inside. Each box has input, output, control and mechanisms, which are presented as arrows around the box. This method focuses on the processes in the system and does not take into account physical hierarchy or parts interaction in the system. In contrast to FFBD, FAST and IDEF0, TRIZ function modeling (Gerasimov *et al.*, 1991) takes into account the physical interaction between the system elements, These interactions, or functions, can be either useful or harmful. Useful functions are then further divided into three performance levels: normal, insufficient or excessive. This method uses a static approach to function analysis. That is, the number of elements and functions, as well as the relationships between them are time-independent and do not change in time.

Yet, many TRIZ practitioners point out the need to identify the problems at each system level more clearly, and to solve them separately. Such a goal was achieved by integrating well-known models and instruments for the system description and function representation. O. Feygenson and N. Feygenson have proposed the Advanced Function Approach in Modern TRIZ (Feygenson and Feygenson, 2016), where they added some steps, such as: “indicate the place the function is performed” and “indicate the time the function is performed.” This approach is also used by the same researchers (Litvin, Feygenson and Feygenson, 2011) concerning application history and the evolution of Function Analysis. Their research indicates that the next logical step for enhancing the Function Approach is to introduce two parameters: "time of performing a function" and "place of performing a function." This method combines previous works in the domain and proposes a consideration of the physical relationships and time-dependence within a system model.

The method presented in this dissertation employs TRIZ Advanced function analysis, referred to as one of the most popular TRIZ tools (Ilevbare, Probert and Phaal, 2013; Spreafico and Russo, 2016), which takes into account the relationship between elements and the degree of these relationships.

2.3 Trimming

Trimming is a formal tool used to improve a system by reducing its complexity (Gadd, 2011). There are different trimming approaches, including step-by-step trimming using three rules (Ikovenko, Litvin, and Lyubomirskiy, 2005), trimming with six rules (Sheu and Hou, 2013) and a system model improvement based on analyzing element importance (Li *et al.*, 2015).

These trimming methods, all of which use formal rules for improving the system step-by-step (Ikovenko, Litvin, and Lyubomirskiy, 2005; Sheu and Hou, 2013; Li *et al.*, 2015), fall into two types: the first (Ikovenko, Litvin, and Lyubomirskiy, 2005; Sheu and Hou, 2013), which is used for design improvement and development, considers functions independently and ranks them by importance. The second type focuses on element importance (Li *et al.*, 2015), rather than function importance, and is used for patent-around design. In this method, a special index is used – a ranking factor. This index defines the importance of the element and highlights the element to trim. In contrast to the first type of trimming, Li's method does not consider function rank.

The ideas described in this literature review have been combined and developed for the approach presented in this dissertation. The primary results of the study are described below.

2.4 CAD and systematic approach collaboration

Some attempts have been made to combine systematic approaches with CAD systems as, for example, TRIZ and CAD in the garment industry (Li, Wang and Lu, 2010), TRIZ, CAD, and customer needs (Sharif Ullah *et al.*, 2016), and TRIZ and SolidWorks (Bakker, Chechurin and Wits, 2011; Chechurin *et al.*, 2011).

There are different methods for design improvement and development, such as topological improvement (e.g., Autodesk Within generative design software (*Generative Design Software. Autodesk Within*, 2017)), and Computer-Aided Invention (CAI; e.g., GoldFire (*Goldfire: Advanced Research, Problem Solving & Analytics*, 2018)), in which the TRIZ approach may also be used. These two methods differ from each other: the topological method, used in additive technologies, proposes topological optimization without generating a new design, while CAI generates a new design but does not transform it into a CAD model. That is, the CAI software uses the function approach, but does not collaborate with engineering software. This technique is used in the patent-around design.

On the other hand, there is collaboration between CAD and Function-Behaviour-State modeling (Gero, 1990). This approach is called system architecting CAD (Komoto and Tomiyama, 2012) and is used in mechatronics. This one uses a V-model (Muller, 2011) for development and has three main parts: decomposition, implementation/integration, and verification/validation.

2.5 Design assessment

Design evaluation is a crucial task in conceptual design since the concept chosen at this stage influences the entire further product life-cycle (Ullman, 2010). Identifying the right concept, however, can be quite difficult, if not impossible. On the one hand, the information regarding concepts is often incomplete, uncertain, and evolving. On the other hand, key decision criteria are often interdependent, which hinders unbiased decision-making. In addition, concepts can have concrete information, e.g. mass, cost, complexity, etc.

Various methods are used for design assessment as, for example, the Analytical Hierarchic Process (AHP; (Saaty, 1980), Quality Function Deployment (QFD; (Yoji, 1994), Comparison (Pugh) matrix (Pugh, 1991), and fuzzy methods (Okudan and Tauhid, 2008). These methods are very different from each other, but have the same purpose – to assess the design criteria set. AHP decomposes a complex problem to sub-problems, each of which is analyzed independently. In this analysis, sub-problem criteria are scored and weighted, that is, ranked in terms of importance. The weights and scores are then calculated to obtain the model's final rank. A Comparison (Pugh) matrix compares the criteria, usually five or more, of each concept with those of a chosen concept (datum). The criteria of the concepts are evaluated against the datum as more (better) than, equal to, or less (worse) than in the datum. Next, the advantages and disadvantages are calculated. Additionally, each criterion can be weighted. In contrast to these methods, QFD is used to translate customer needs into engineering requirements, but can also be used in concept selection in conjunction with, for example, a Pugh matrix. In this case, "House of Quality," a basic design tool of QFD, is used. This tool measures the importance of customers' desires and creates a link between desire and relevant engineering characteristics. This process uses system hierarchy, which can be applied to subsystems and components of the system. Also, QFD makes it possible to define the relationships between design criteria. These relationships can be positive or negative. The fuzzy methods allow a range of values for the design assessment. Moreover, they can be presented as triplet values (Kaufmann and Gupta, 1985) and ranking can be calculated using Fuzzy Heavy Weighted Averaging (Collan and Luukka, 2016). The method in this dissertation weights criteria, considers system hierarchy, and is similar to AHP. This approach is very useful when values are uncertain.

In this dissertation, the Comparison (Pugh) Matrix and AHP (Salonen and Perttula, 2005), both well-known in Finland, are used. These methods are semi-automated. For the assessment, two sets of criteria are used: those defined by the user and those defined by the 3D CAD model. The first set includes complexity, ergonomics, etc. The second set consists of a mass, production cost, number of elements, etc. All of these criteria have certain values and fuzzy criteria are not used.

The 3D CAD model defined criteria are translated by using special software, i.e., SolidWorks API (*API Support*, 2017).

3 Validation method

For this dissertation, a special survey was conducted in order to validate the results. Ten engineers at two companies, Termotronic and Institute Telecomunikatsii, in Saint-Petersburg, Russia, were surveyed. These engineers used the method presented in this dissertation in actual industrial cases in mechanical engineering. The method was semi-automatic, which means that function modeling, ranking, and trimming were completed without special software, but for the decomposition, unique software was used. As the source, a SolidWorks CAD model was used.

The survey asked the following five questions:

- Question 1: Do you generate new design ideas using the presented method?
- Question 2: Is this method easy to use and understand?
- Question 3: Rate the difficulty of using the suggested approach for your design.
- Question 4: Rate the difficulty of creating a function model.
- Question 5: Rate the difficulty of interpreting results.

In addition, each inteviewee wrote short comments. Each question was rated on a 5-point scale, where 1 is absolutely no/very difficult and 5 is absolutely yes/very easy. For example, if an engineer found the method very straightforward, the answer to question 2 was “5,” and if he/she thought the method was very complicated, the answer was “1.” The survey results are presented in Table 2. The comments are not presented in this chapter and were used only to help define the features or disadvantages of the method more concretely. The result is calculated as the arithmetic mean of all scores.

Table 2 - Survey results

	Question 1	Question 2	Question 3	Question 4	Question 5
Engineer 1	4	2	2	3	5
Engineer 2	5	1	1	4	4
Engineer 3	4	1	2	3	4
Engineer 4	5	3	3	5	5
Engineer 5	5	2	2	3	3
Engineer 6	4	2	3	3	5
Engineer 7	5	1	2	4	4
Engineer 8	5	1	2	4	4
Engineer 9	4	3	2	3	4
Engineer 10	3	1	1	2	3
Result	4.4	1.7	2	3.4	4.1

Brief comments and a discussion of this survey are presented in chapter 6.

4 Method description

The method presented in this dissertation comprises an algorithm for product development at the conceptual design stage. The suggested approach consists of four procedures: 3D modeling, function analysis, trimming, and design assessment. The method diagram is presented in Figure 1.

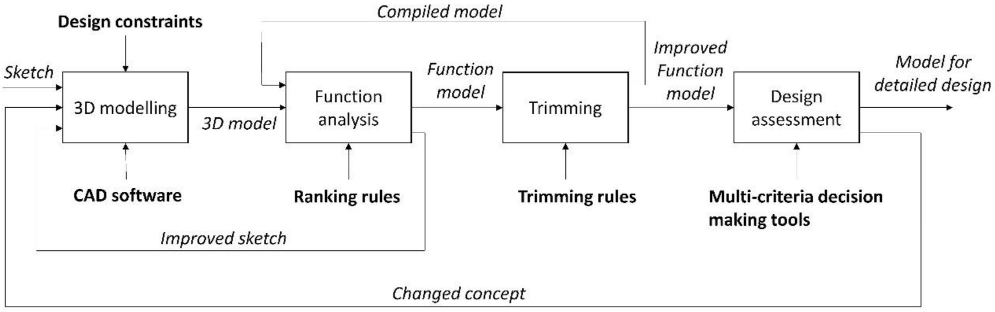


Figure 1 - Method diagram

The development starts with a sketch of a new design. The developer then creates a 3D model using special CAD software (e.g., SolidWorks, Kompas, Inventor, Catia) and follows with a function analysis, thereby transforming the 3D CAD model into a function model of the system. At this point, the user can choose the complexity of the function model. In other words, the developer chooses a decomposition level, which can be different for different parts of the system. For example, a developer can combine a few parts or subassemblies in the assembly. If the functional representation is very complicated, the function model may be changed. Further, the system model is simplified, i.e., system complexity is reduced, by removing a few system parts. This step is called trimming. Implementing the result, however, is very difficult because the developer needs to transform the improved function model into a new CAD model manually. Indeed, design constraints sometimes do not permit this transformation. In such cases, the developer needs to change the function model. Once the trimming step is completed, the improved function model is evaluated using the multi-criteria decision-making tools.

It is essential to use the special, formal rules and definitions in the presented method. In TRIZ function modeling, the functions are presented in the following manner: the tool (the function carrier), the function, and the object. The function must represent a real action from tool to object. For example, “a helmet deflects a bullet” is a legitimate function, while “a helmet protects a head” is not. On the other hand, the function cannot be declarative, e.g., “a pill improves health.”

To define the importance of a function in a system, a formal index called function rank is used wherein the importance of a function is determined by its role in the main function. A rank is an integer number inversely proportional to the function's importance. For instance, a function with rank three is more important than a function with rank five.

The ranking factor is a formal index that defines the function's rank. It is a rational number and may be positive or negative. It is also inversely proportional to the function's importance. Thus, the smallest ranking factor value defines the most necessary function.

The object of the main function is called a Target, which is an element that defines the purpose of the system in the initial function model.

4.1 3D modeling

This section describes a formal step where a paper sketch or idea is transformed into a 3D CAD model. In this dissertation a top-down approach for SolidWorks is used (*SolidWorks - Design Methods (Bottom-up and Top-down Design)*, 2013). Here the main parts, without detailing, are presented in an assembly in order to create the overall system structure. The Software can be used with a special application programming interface (API) that automates the model information transfer. This information is used as the input to the function analysis step.

The SolidWorks software used for 3D modeling in this dissertation was chosen for its friendly interface. Also, information about the API usage was easily available on the internet. A 3D CAD model of an assembling holder is presented in Figure 2. This model is illustrative, but was inspired by actual industrial case studies. The example below is used in the method description.

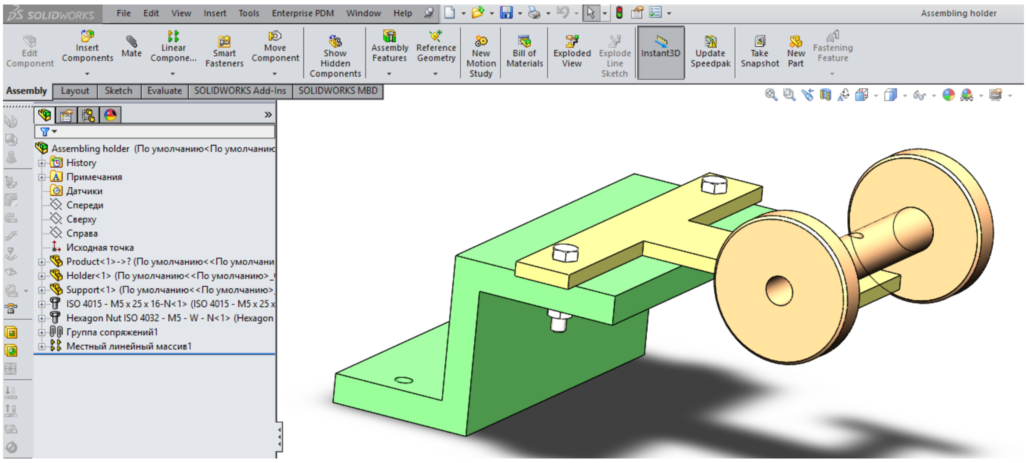


Figure 2 - Assembling holder model

4.2 Function analysis

Function analysis is a formal method in modern TRIZ. It defines the main parts of the system, their interactions, type, and degree of each interaction. This approach consists of three sub-steps: component analysis, interaction analysis, and function modeling.

The component analysis concerns the decomposition of the system model to its main parts, e.g., for large assemblies. This step may be done using the CAD model analysis (Efimov-Soini and Chechurin, 2017). This analysis is done by using the SolidWorks API and specialized software. The interaction between elements is defined at the interaction analysis step. At this step, the 3D CAD model converts to the unique software names of the elements, system hierarchy, and mates. The software creates an interaction table by analyzing the mates and 3D CAD model structure. In the final step, a function diagram (function model) is created, and the rank (importance) of the functions in the system is defined. Special software created in C# Visual Studio 2017 using the SolidWorks API tool completes the conversion.

4.2.1 Component analysis

This step decomposes the system into its elements and highlights the target. The component analysis process is shown in Figure 3

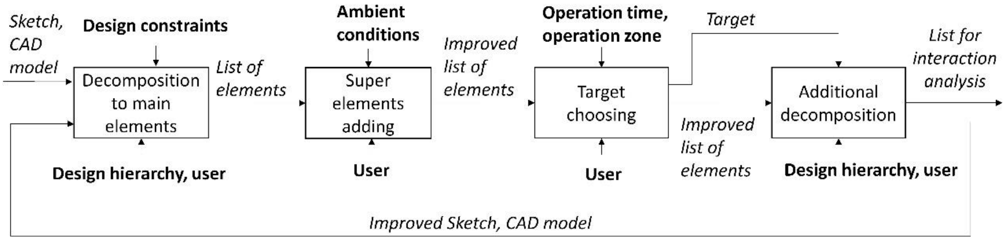


Figure 3 - Component analysis process

First, a CAD model or product sketch is used to decompose the system model to its main elements. This is done manually or semi-automatically using design hierarchy. A complex system is usually decomposed into large assemblies, e.g., the body, electrical system, engine, etc., of a car, and a simple system into its parts. Then, specialized software is used to collect the information from the CAD model. This approach makes it possible to automate the decomposition process.

Second, the list of elements is supplemented with new elements: elements of the super system or other elements. These may be elements from the environment, e.g., gravity or electromagnetic field. On the other hand, a user may add some elements that interact with the system, e.g., a road is not included in the car model but can be used in the function analysis. These elements are not included in the initial CAD model or the sketch.

An industrial case study illustrates the approach suggested in this dissertation. The assembling tool model, presented in Figure 4, consists of the product and an individual holder to hold it in assembling position. This holder is attached to a support with two nuts and two bolts. The support is also used to hold this system on the table.

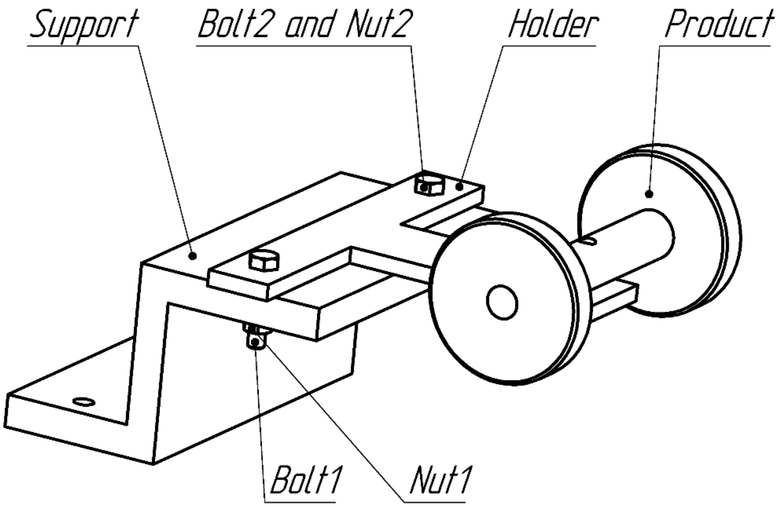


Figure 4 - Components of the model

Next, the developer chooses the target. This element defines the main function of the system, and is chosen by defining the operation time and operation zone. This means the target is usually an element which performs the main function in the system. For example, in the system "electric drill drills wall," the bore is the target. In the system presented here, the target is the product.

Finally, in the last decomposition procedure, assemblies are decomposed into smaller parts: subassemblies, parts, edges, etc. The primary goal of this step is to create a detailed system decomposition model in the area close to the target. The final list of elements is not always suitable for future development, in which case the user must improve the initial CAD model or sketch, and repeat the component analysis process. If the system is simple, no further decomposition is needed.

4.2.2 Interaction analysis

At this step, relationships between the elements in the system model are defined using the interaction matrix (Ikovenko, Litvin, and Lyubomirskiy, 2005).

A special interaction matrix is used for the interaction analysis. In this matrix, the interaction between elements in the system model is denoted by a plus sign (+), and lack of interaction with a minus sign (-). The interaction matrix for the assembling tool is presented in Table 3.

This procedure may be done manually or semi-automatically. In the case study, special software uses the SolidWorks "Mates" tool to analyze the CAD model. The SolidWorks, geometric mate "coincidence" is equal to the function "hold" in many ways. Some elements must be added to the matrix manually as, for example, the element "table" in the system. This element is not included in the 3D CAD model, but the table may be used in the proposed method.

Table 3 – The interaction matrix.

	Support	Bolt1	Nut1	Bolt2	Nut2	Holder	Product	Table
Support	■	+	-	+	-	+	-	+
Bolt1	-	■	+	-	-	+	-	-
Nut1	-	+	■	-	-	+	-	-
Bolt2	-	-	-	■	+	+	-	-
Nut2	-	-	-	+	■	+	-	-
Holder	+	-	+	-	+	■	+	-
Product	-	-	-	-	-	+	■	-
Table	+	-	-	-	-	-	-	■

4.2.3 Function modeling

The interactions between elements are defined as functions at the function modeling step. The function rank of each one is defined by its importance. The following definitions are used in this dissertation:

- The rank defines the function importance. The rank is evaluated by integers from 0 to ∞, where the function with the highest rank has the value 0. Hence, the higher the number, the lower the rank.
- The more useful (or more used) the functions or elements are, the higher their rank; useless (or unused) functions or elements have a lower rank.
- The main function has an initial rank 0.
- The rank is defined by the ranking factor. The lower the ranking factor, the higher the rank.
- For functions with the same ranking factor, the distance between the element associated with the function and the target is additionally taken into account. These ranking factors are marked with letters A, B, C, etc.,

where letter A indicates a function with the smallest distance to the target. Therefore, the rank for the function with the letter A is higher than for the function with the letter B.

In this method, function ranking is based on function importance and the number of interactions among function elements. The primary definitions of the presented approach are the following:

- The closer the function is to the main function, the higher is its rank. This step is similar to the GEN3 ranking method.
- The element with the highest number of connections is the most important for the system. All functions associated with this element have a high rank.
- Duplicated functions have a lower rank. For example, if two bolts are holding one stator end plate, the function "hold" for each bolt has a lower rank.
- The farther away an element is from the key element geometrically, the lower its rank.

There are six sub-steps in the interaction analysis: defining interaction as a function, initial ranking, initial creation of the function model, selecting the model, final ranking, and analysis of function interactions.

During sub-step one, “defining interaction as a function,” each interaction is, obviously, defined as a function. If the interaction between elements is not available, the function is not defined. Functions in the system model are presented in Table 4.

Table 4 - Functions in the system model

Element 1	Function	Element 2	
Support	Holds	Holder	
Support	Holds	Bolt1	
Support	Holds	Bolt2	
Table	Holds	Support	
Bolt1	Holds	Nut1	
Bolt1	Holds	Holder	
Nut1	Holds	Holder	
Bolt2	Holds	Nut2	
Bolt2	Holds	Holder	
Nut2	Holds	Holder	
Holder	Holds	Product	Main function

The main function and the target are also defined in this step. In the case study, the main function is “holder holds product,” and the target is “product.”

Next, at sub-step two, the initial function rank is defined. Each function rank (importance) is defined on the interval [0…+∞), with 0 being the initial function rank of the main function and the highest number for the least important element in the system. In other words, initially, the main function is the most important function in the system. In the suggested system, the initial ranking is presented in Table 5.

Table 5 - Initial ranking

Element 1	Function	Element 2	Rank
Support	Holds	Holder	1
Support	Holds	Bolt1	3
Support	Holds	Bolt2	3
Table	Holds	Support	2
Bolt1	Holds	Nut1	2
Nut1	Holds	Holder	1
Bolt2	Holds	Nut2	2
Nut2	Holds	Holder	1
Holder	Holds	Product	0

At sub-step 3, a function model is created using the results of the initial ranking. In fact, it is possible to create a function model, sub-step 4, simultaneously with the initial ranking. In the function diagram, the elements are marked as rectangles. The target is placed on the right side, which is recommended. Elements that are impossible to modify or are not included in the model, but create an action (e.g., gravitation), are denoted with a hexagon. The suggested function model is shown in Figure 5.

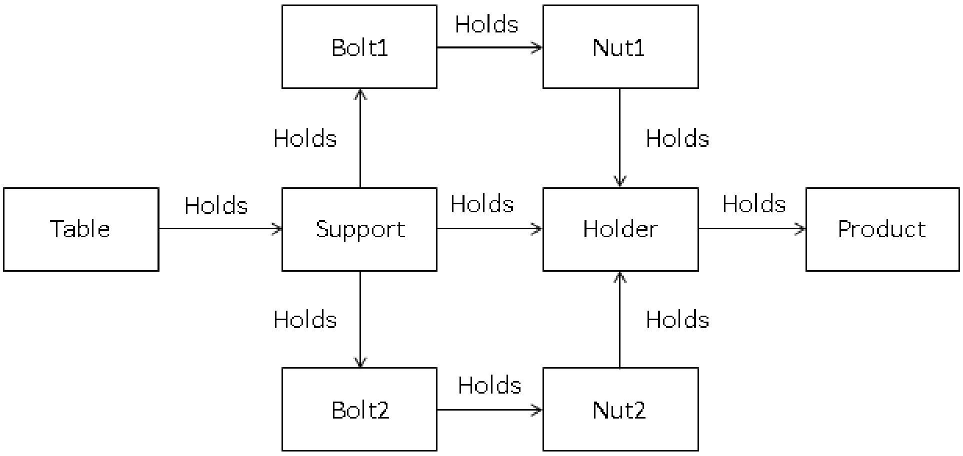


Figure 5 - Initial function model

In the suggested method, two model types are presented: static and dynamic. In the static model, the function rank (importance), the interaction number in the system, and the element number in the system are permanent. On the other hand, one or all parameters change in the dynamic model. The dynamic model is presented as a set of system snapshots. Each snapshot is a static state of the system. Thus, the function rank, numbers of interaction, and the number of the element are permanent in each state. For each static state, the time (duration) of each snapshot is defined using the following formula:

$$t_{ni} = \frac{t_i}{t_w} \qquad (1)$$

Where t_{ni} is the normalized time of the state i, t_i – the time of the state (in minutes, seconds, years, etc.), and t_w is the total observation time (in minutes, seconds, years etc).

At sub-step 5, the presented approach is used to calculate the final function rank, which uses a unique formal index (the ranking factor). This is inversely proportional to the function importance. Thus, a ranking factor with a smaller value defines an essential function. The final ranking factor is defined by using normalized time:

$$FFR = \sum FR_i \times t_{ni} \qquad (2)$$

Where FFR is the final ranking factor, FR_i is the ranking factor in the state i, and t_{ni} is the normalized time of the state i for the static system t_{ni}=1.

The dynamic and static approach may be used for the assembling holder system. For the dynamic approach, two states are considered: the product is on the assembling tool (tn_1=0.9) and the waiting mode when the product is left on the table (tn_2=0.1). The values tn_1, tn_2 are defined randomly, but these values were inspired by actual industrial case studies – in real production, waiting time is less than working time, and in the ideal production case $tn_2 \rightarrow 0$.

A unique index, called the ranking factor, is added to define the function rank at the final ranking sub-step. The following formula is used to calculate this:

$$FR_i = R - N_l + N_d \qquad (3)$$

Where FR_i is the ranking factor in this state, R is the initial rank, N_l is the number of function carrier links, and N_d is the number of duplicated functions. The final ranking is presented in Table 6.

Table 6 - Final ranking

Element1	Function	Element2	R	Nl	Nd	FR	Final rank
Support	Holds	Holder	1	3	0	-2	1
Support	Holds	Bolt1	3	3	1	1	3A
Support	Holds	Bolt2	3	3	1	1	3A
Table	Holds	Support	2	1	0	1	3C
Bolt1	Holds	Nut1	2	1	1	2	4
Nut1	Holds	Holder	1	1	1	1	3B
Bolt2	Holds	Nut2	2	1	1	2	4

Nut2	Holds	Holder	1	1	1	1	3B
Holder	Holds	Product	0	1	1	0	2

Additional sub-indexes, such as 3A, 3B, and 3C, are used in the case study. The letters are used to distinguish functions with the same ranking factor. Thus, a function with sub-index A is geometrically closer than the function with sub-indexes B and C. Therefore, the element “support” is closer to the element “product” than are the elements “nut1” and “nut2.”

The situation is different in the dynamic approach. There are two system states, such as the product in the assembling tool (tn_1=0.9) and the waiting mode when the product is not installed in the assembling tool (tn_2=0.1). The first function model state is equal to the model in the static approach. The function model (tn_2) in the waiting mode is presented in Figure 6.

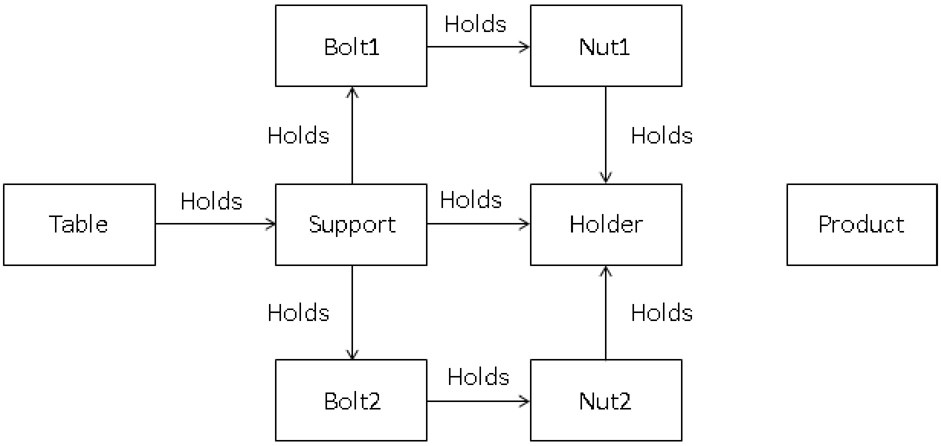


Figure 6 – The function model for the state tn2.

In the presented state, the function "holder holds product" is not available because these elements do not interact here. The ranking table for this state is presented in Table 7.

Table 7 - Ranking in dynamic approach

Element1	Function	Element2	R_1	R_2	N_{l1}	N_{l2}	N_d	FR_1	FR_2	Final rank
Support	Holds	Holder	1	1	3	3	0	-2	-2	1
Support	Holds	Bolt1	3	1	3	3	1	1	-1	3A
Support	Holds	Bolt2	3	1	3	3	1	1	-1	3A
Table	Holds	Support	2	0	1	1	0	1	-1	3B
Bolt1	Holds	Nut1	2	2	1	1	1	2	2	5A
Nut1	Holds	Holder	1	3	1	1	1	1	3	4

Bolt2	Holds	Nut2	2	2	1	1	1	2	2	5A
Nut2	Holds	Holder	1	3	0	1	1	1	3	4
Holder	Holds	Product	0	NA	1	1	0	-1	0	2

At sub-step 6, sets of functions are defined after the ranking. This approach makes it possible to improve the trimming process and obtain new design patterns. At this sub-step, functions are divided into three types: independent (-), dependent (+), and equal (=). Independent functions do not interact, e.g., in a fan system installed in the wall, the functions “wall holds fan” and “fan moves air” are independent. In the dependent type, functions create a result “together,” e.g., “bolt holds nut” and “nut holds plate” are dependent functions. The same functions create a similar result in a system, e.g., the functions “welding holds plate” and “bolt holds plate” are often equal. In the case study, the independent functions were trimmed separately, and dependent and similar functions are in sets.

The function interaction matrix for the assembling tool model is shown in Table 8.

Table 8 – The function interaction matrix

	Support holds holder	Support holds bolt1	Support holds bolt2	Table holds support	Bolt1 holds nut1	Nut1 holds holder	Bolt2 holds nut2	Nut2 holds holder	Holder holds product
Support holds holder	■	+	+	-	-	+	-	+	-
Support holds bolt1	+	■	=	-	-	-	-	-	-
Support holds bolt2	+	=	■	-	-	-	-	-	-
Table holds support	-	-	-	■	-	-	-	-	-
Bolt1 holds nut1	-	-	-	-	■	+	=	-	-
Nut1 holds holder	+	-	-	-	+	■	-	=	+
Bolt2 holds nut2	-	-	-	-	=	-	■	-	-
Nut2 holds holder	+	-	-	-	-	=	-	■	+
Holder holds product	-	-	-	-	-	+	-	+	■

There are two function sets: the dependent set “table holds product,” and the set of equal functions “bolt1 and nut1 hold support” and “bolt2 and nut2 hold support.”

4.3 Trimming

Trimming is a formal method for improving a design by reducing system complexity. The method here is based on a previous development (Ikovenko, Litvin and Lyubomirskiy, 2005; Li *et al.*, 2015). At this step, a distinction is made between independent, dependent and similar functions. Three formal rules are used for the independent functions. The same rules are used for dependent and similar functions, but the trimming for these functions are completed in a set. That is, the dependent and similar function sets are trimmed as one function.

The three formal rules follow. A function may be trimmed if:

A) An object of the Function does not exist.

B) An object of the Function performs the function itself.

C) Another Engineering System Component performs the useful function of the Function Carrier.

The trimming procedure starts with a function with a lower rank. If the function sets are defined in the system model, then the trimming process starts with the last one. Three formal rules are used to trim sets in the trimming process. This is a radical method, but a new qualitative design may be created.

In the assembling tool, the trimming process has the following steps:

- Functions “bolt1 holds nut1,” “nut1 holds holder,” and “support holds bolt1” (sets“bolt1 and nut1 hold support” and “bolt2 and nut2 hold support”) may be trimmed if the function is transferred. The function “hold” is transferred to bolt2, nut2, and holder in a soft reduction, or to the holder in a radical trimming approach. The result of this approach is presented in Figure 7
- The set “table holds product” may be trimmed radically by using rule A. In the case study, the product is holding itself on the table using a special pad in the product. The trimming result is presented in Figure 8. This one is similar to the TRIZ tool called “Ideal final result.” In this approach, the tool is not available, but the function is performed.

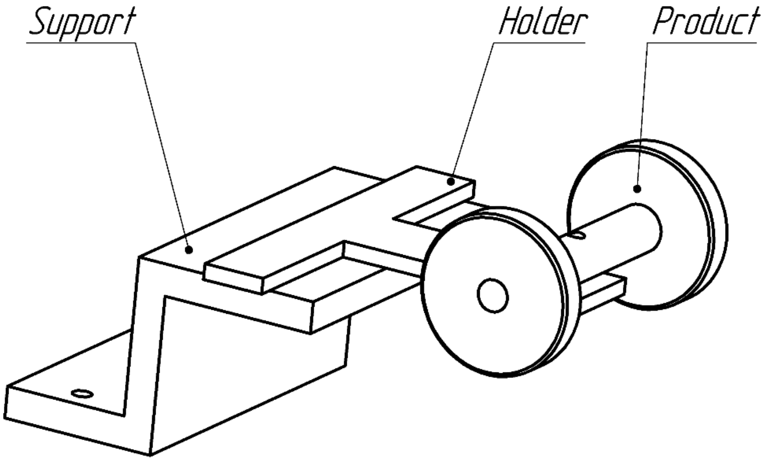


Figure 7 - Improved design

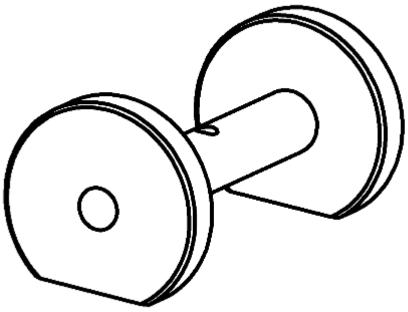


Figure 8 – Improved product model.

4.4 Design assessment

The research method presented in this dissertation is divided into two main parts: development and assessment. For assessment, multi-criteria decision-making methods (MCDM) are used. This section is devoted to the two most popular verification methods in Finland, Pugh’s matrix and AHP. Three designs are compared: the initial design (Figure 2), the improved design (Figure 7), and the improved product (Figure 8).

The function model and CAD model are integrated for use in the design assessment. This integrated model serves as the source in the design assessment tool. This means that the user can add information from the function model, CAD model or manually. The information may be either uncertain (e.g., beauty, usability) or specific (complexity, mass, manufacturing cost). The specific parameters are transferred using special software with API (*API Support*, 2017) and C# language (Hejlsberg, 2011). This interface is integrated into the SolidWorks software.

In the case study, both manual and automatic techniques were used. Uncertain criteria (usability, maintainability, ergonomics, etc.) were added manually – the user manually added parameter arguments – and the specific information (mass, complexity, manufacturing cost, etc.) was transferred automatically using special SolidWorks tools (measuring, costing, etc.). The complexity parameter was solved by using the Pugh Complexity Factor (Pugh, 1996) and the design function model.

The design assessment for the matrix is presented in Table 9. In a Pugh table, the improved design and improved product are compared to the initial design, whose parameter values are noted as “datum,” using five parameters: weight, cost, complexity, ergonomics, and maintainability. The software compares the parameter values for the initial design and selected design(s) in this process. A plus sign (+) implies a value better than for the initial design, a minus sign (-) shows that the value is worse, and the equal sign (=) means the parameter values are equal.

Table 9 - Pugh assessment table

Criteria	Initial design	Improved design	Improved product
Weight	D	=	+
Cost	A	-	+
Complexity	T	+	+
Ergonomics	U	+	+
Maintainability	M	+	+
+		3	5
-		1	0
=		1	0
Rank	3	2	1

The other assessment method, AHP, is shown in Table 10. In this approach, each parameter is presented using values 1-9. The weight and cost values here are from the CAD, complexity is from the function model and, finally, ergonomics and maintainability are peer-assessment values, chosen from the expert and user surveys.

Table 10 - AHP assessment table

Criteria	Initial design	Improved design	Improved product
Weight	2	1	9
Cost	2	1	9
Complexity	1	3	9
Ergonomics	1	3	9
Maintainability	1	5	9
Sum	1.4	2.6	9
Rank	3	2	1

Using two different assessments makes it possible to choose the best concept. In the case study, the improved product (Figure 8) is the most acceptable concept.

4.5 Method description summary

The suggested approach comprises CAD sketch development, function analysis, system complexity reduction and final design assessment. In this approach, from a simple sketch or CAD model a developer can obtain new original concepts or radically change the product design.

The method is based on scientifically proven instruments (system analysis, mathematics, logic) as well as on design instruments (CAD, TRIZ, MCDM) that have been given wide application and approval in engineering practice. The validity of the method is also proven by some practical trial applications, presented in the dissertation as case studies. Finally, a survey conducted among professional engineering designers confirmed the efficiency of the approach.

5 Results

In this dissertation, a method for developing conceptual designs is proposed that uses a preliminary CAD model as the source and returns a new or improved CAD model for detailed design as output. Most of the process is automatic or semi-automatic. The suggested approach uses SolidWorks API to transfer system hierarchy and interactions between elements to the function model; an algorithm based on TRIZ function ranking to define function importance; the TRIZ trimming tool to improve the design by reducing system complexity; and MCDM methods (Pugh matrix and AHP) to assess the design. Turning the final function model into a CAD model for detailed design is carried out manually.

The suggested method makes it possible to obtain a new original design using an initial CAD model. The user can choose the “degree” of model improvement. That is, the developer can choose between limited system optimization and radical system reduction for a new design.

In this research, two different designs were developed using the initial CAD model. The first model is a complexity design reduction without an invention paradigm change. This is similar to the results of Design for the Manufacturing and the Assembly (Boothroyd, Dewhurst and Knight, 2002). The second model is a radical change of the model and design idea. This is similar to the results of a TRIZ tool called Ideal Final Result (Altshuller, 1984).

The research objectives have been fully achieved and a formal method for engineers and developers has been presented. All research questions have been solved. The evolution of the work and solutions to the questions are presented in articles I-VI and section 1.3 of the dissertation.

Also, this research answers all of the questions raised in section 1.2. The answers are in the text of the manuscript and summarized in Table 11, below.

Table 11 - Brief answers to the research questions

Research question	Brief answer
What structured approaches are used for generating ideas? What approaches improve these ideas?	A good approach is TRIZ. There are some works in the domain concerning collaboration between TRIZ and conceptual design; it is easy to use and understand.
What are the methods for assessing ideas/concepts?	Best idea: use MCDM methods such as Pugh matrix and AHP because they are most popular in Finland.
How can the development tools identified in the research collaborate with CAD	The best way was inspired by the set of works of Bakker, Wits, and

software? Have similar studies been carried out?	Chechurin.
How to transform existing sketches/ideas/CAD models into a TRIZ function model for further modification?	By customizing an existing method – Function Analysis. The initial method does not take into account the relationships between system elements.
How to modify information from sketches or CAD models to receive new design possibilities?	By customizing an existing method – Trimming. The initial method does not take into account the evolution of the system.
How to evaluate the results obtained using the presented method?	Best idea – use MCDM methods such as AHP and Pugh matrix. Results were confirmed in an industrial case study.

The presented method was verified during the creation/improvement of 18 industrial tools developed at two companies, Termotronic and Institut Telecomunicatsiy, in Saint-Petersburg, Russia. It was used at the conceptual design stages in 13 cases, and to improve the existing design in eight cases, with the method being used for both purposes in three cases.

6 Research limitation and discussion

This chapter discusses the research limitations and briefly describes how they might be resolved. There are two fundamental limitations affecting this research. The first regards the area of application and the second concerns the CAD software used to create the initial model.

The area of application was limited to mechanical engineering because the tool presented in this dissertation is aimed at developments in mechanical engineering and because the author is a mechanical engineer. Therefore, the method was tested only with mechanical engineers and developers. In addition, all of these specialists have basic knowledge of TRIZ. This was important since the presented system requires a good understanding of product structure and the relationships between product parts in industrial developments and, thus, is not very friendly to a novice. To better understand the disadvantages of the method, experienced engineers were chosen.

The research was also limited by the fact that only SolidWorks software was used in the research, while other CAD software products were not studied. SolidWorks was chosen because the author has extensive experience using it. The main problem in this research was how to translate the CAD model into a TRIZ function model. To do this, the SolidWorks “Mates” tool was used, but in the other software, since the interaction tools and types of interaction are not similar to SolidWorks, additional development would have been necessary. Using SolidWorks, therefore, meant that the main problem was how to translate this interaction to a function model using API and not in understanding how to interact assemblies, subassemblies, and parts in the CAD model. In the Autodesk Inventor API (*Inventor 2018 Help: Getting Started with Inventor’s API*, 2018), for example, the types of objects, features, and relationships between objects are not similar to those of SolidWorks API.

To resolve these problems, additional research and funds are needed. First, the current tool can be challenging for inexperienced CAD and TRIZ users. Moreover, the presented method should be expanded to other technical areas, which requires adding another experienced specialist. It should be noted that a similar study has been done in the construction area (Renev, Chechurin and Perlova, 2017). Also, to develop the tool for use with other CAD software, other specialists in this area are needed since the API information structures vary greatly with different CAD software products.

The results of a unique survey taken to verify the algorithm presented in this dissertation are presented in Table 2. In this survey, ten engineers from two companies (Termotronic and Institut Telekomunicatsiy) improved their existing systems using the suggested method. They worked in a semiautomatic manner, without any unique tools for trimming systems or ranking functions, to better understand the weakness of the approach. All of the specialists noted the new design patterns they obtained using this method. Eight of ten engineers noted that the calculation in complex assemblies was very difficult and seven of ten noted the ambiguity of the functional definition.

Finally, a vital disadvantage of the present method is the absence of an automated link between the final function model and the final CAD model. A user must create the final CAD model manually, which means that the method cannot be used by unskilled TRIZ and CAD users.

7 Conclusion

The method presented in this dissertation makes it possible to improve a system model using the system function presentation. This takes into account the evolution of the situation (and therefore its function model) and shows how the approach yields trimming ideas that are different from what can be derived from the standard static function ranking procedure. With this method a developer can obtain a new original design or radically change the existing design. Also, introducing the time domain is believed to make the function analysis more accurate and realistic. This last is expressed as a formula and requires some calculations, but makes it possible to create improvements in a systematic manner. Thus, improving the method and introducing it into the most popular CAD software can change the process of development, which is similar to integrating finite-elements methods in CAD software. This means the developer will design concepts, taking into account the function presentation of the system to create the most acceptable design, in CAD software – without other tools and special knowledge. In addition, engineers will choose between concepts in common frameworks. Further integration with PDM/PLM systems can radically improve the development process in research and development activities.

The method can be applied in both industry and science. Using this method, engineers created 18 special assembling tools. Examples of using this method in industrial applications are presented in articles I-IV. In addition, some examples of applications were studied at LUT Summer school 2017 and 2018 in the Basic TRIZ course.

References

Akiyama, K. (1991) *Function Analysis: Systematic Improvement of Quality and Performance*. Cambridge MA: Productivity Press Inc.

Altshuller, G. (1984) *Creativity As An Exact Science*. New York: Gordon And Breach.

Altshuller, G. and Shapiro, R. (1956) 'Psychology of inventive creativity', *Issues Psychological*, 6, pp. 37–49.

API Support (2017). Available at: https://www.solidworks.com/sw/support/api-support.htm.

Autodesk. Introduction to Concept Modeling. (2018). Available at: https://knowledge.autodesk.com/support/alias-products/getting-started/caas/CloudHelp/cloudhelp/2019/ENU/Alias-Tutorials/files/GUID-9C1D61CC-902C-413F-89D2-58268469F0F5-htm.html.

Bakker, H. M., Chechurin, L. S. and Wits, W. W. (2011) 'Integrating TRIZ function modeling in CAD software', *Proceedings of TRIZfest-2011*, p. 18. Available at: www.matriz.org.

Bilda, Z. and Gero, J. (2005) 'Do We Need CAD during Conceptual Design?', *Computer Aided Architectural Design Futures 2005*, pp. 155–164. doi: 10.1007/1-4020-3698-1_14.

Boothroyd, G., Dewhurst, P. and Knight, W. (2002) *Product Design for Manufacture and Assembly*. 2nd edn. New York: Marcel Dekker.

Bytheway, C. (2007) *FAST Creativity & Innovation*. J.Ross Publishing.

CATIA 3D Master Conceptual Design (2018). Available at: https://www.intrinsys.com/software/tv/catia/3d-master-conceptual-design (Accessed: 4 August 2018).

Chechurin, L. (2016) 'TRIZ in Science. Reviewing Indexed Publications', *Procedia CIRP*, 39, pp. 156–165. doi: 10.1016/j.procir.2016.01.182.

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.

Collan, M. and Luukka, P. (2016) 'Strategic R&D Project Analysis: Keeping It Simple and Smart', in *Fuzzy Technology.Present Applications and Future Challenges.*, pp. 169–191. doi: 10.1007/978-3-319-26986-3_10.

Efimov-Soini, N. and Chechurin, L. (2017) ‘The Method of CAD Software and TRIZ Collaboration’, in Kravets, A. et al. (eds) *Communications in Computer and Information Science*. Volgograd, Russia: Springer International Publishing, pp. 517–527. doi: 10.1007/978-3-319-65551-2_38.

Feygenson, O. and Feygenson, N. (2016) ‘Advanced Function Approach in Modern TRIZ’, in *Research and Practice on the Theory of Inventive Problem Solving (TRIZ)*. Cham: Springer International Publishing, pp. 207–221. doi: 10.1007/978-3-319-31782-3_12.

Fuge, M. *et al.* (2012) ‘Conceptual design and modification of freeform surfaces using dual shape representations in augmented reality environments’, *Computer-Aided Design*, 44(10), pp. 1020–1032. doi: 10.1016/j.cad.2011.05.009.

Gadd, K. (2011) *TRIZ for Engineers: Enabling Inventive Problem Solving*. First Edit. John Wiley & Sons, Ltd. Published.

Generative Design Software. Autodesk Within (2017). Available at: http://www.autodesk.com/products/within/overview.

Gerasimov, V. *et al.* (1991) *Basics of Function-Cost Analysis approach. Guidlines (in Russian).* Moscow: Moscow, InformFSA.

Gero, J. S. (1990) ‘Design Prototypes: A Knowledge Representation Schema for Design’, *AI Magazine*, 11(4), p. 26. doi: 10.1609/AIMAG.V11I4.854.

Di Gironimo, G. *et al.* (2013) ‘Improving concept design of divertor support system for FAST tokamak using TRIZ theory and AHP approach’, *Fusion Engineering and Design*. doi: 10.1016/j.fusengdes.2013.07.005.

Goldfire: Advanced Research, Problem Solving & Analytics (2018). Available at: https://www.ihs.com/products/design-standards-software-goldfire.html.

Hasby, F. M. and Roller, D. (2016) ‘Sharing of Ideas in a Collaborative CAD for Conceptual Embodiment Design Stage’, *Procedia CIRP*, 50, pp. 44 – 51. doi: 10.1016/j.procir.2016.04.131.

Hejlsberg, A. (2011) *The C# programming language*. Addison-Wesley.

Ikovenko, S., Litvin, S. and Lyubomirskiy, A. (2005) *Basic training course.* Boston: GEN3 Partners.

Ilevbare, I. M., Probert, D. and Phaal, R. (2013) ‘A review of TRIZ, and its benefits and challenges in practice’, *Technovation*, 33, pp. 30–37. doi: 10.1016/j.technovation.2012.11.003.

Inventor 2018 Help: Getting Started with Inventor's API (2018). Available at: http://help.autodesk.com/view/INVNTOR/2018/ENU/?guid=GUID-4939ABD1-A15E-473E-9376-D8208EC029EB (Accessed: 3 September 2018).

Kaufmann, A. and Gupta, M. (1985) *Introduction to fuzzy arithmetic: Theory and applications*. Van Nostrand Reinhold Co.

Komoto, H. and Tomiyama, T. (2012) 'A framework for computer-aided conceptual design and its application to system architecting of mechatronics products', *CAD Computer Aided Design*, 44(10), pp. 931–946. doi: 10.1016/j.cad.2012.02.004.

Kucherov, A. S. *et al.* (2014) 'Methodology of spacecraft conceptual design definition based on problem-oriented systems and CAD/CAE technologies integration', in *AIP Conference Proceedings*. American Institute of Physics, pp. 523–527. doi: 10.1063/1.4904619.

Li, M. *et al.* (2015) 'A TRIZ-based trimming method for patent design around', *CAD Computer Aided Design*. Elsevier Ltd, 62, pp. 20–30. doi: 10.1016/j.cad.2014.10.005.

Li, W. L., Wang, J. and Lu, G. D. (2010) 'TRIZ in 3D Garment CAD', *Advanced Materials Research*, 102, pp. 50–54. doi: 10.4028/www.scientific.net/AMR.102-104.50.

Litvin, S., Feygenson, N. and Feygenson, O. (2011) 'Advanced function approach', *Procedia Engineering*. Elsevier, 9, pp. 92–102. doi: 10.1016/J.PROENG.2011.03.103.

Luo, Y., Shao, Y. and Chen, T. (2012) 'Study of New Wall Materials Design Based on TRIZ Integrated Innovation Method', *Management Science and Engineering*, 6(4), pp. 15–29. doi: 10.3968/j.mse.1913035X20120604.635.

Muller, G. (2011) *Systems architecting : a business perspective*. CRC Press. Available at: https://www.crcpress.com/Systems-Architecting-A-Business-Perspective/Muller/p/book/9781439847626 (Accessed: 16 July 2018).

Noon, C. *et al.* (2012) 'A system for rapid creation and assessment of conceptual large vehicle designs using immersive virtual reality', *Computers in Industry*, 63(5), pp. 500–512. doi: 10.1016/j.compind.2012.02.003.

Okudan, G. E. and Tauhid, S. (2008) 'Concept selection methods - a literature review from 1980 to 2008', *International Journal of Design Engineering*, 1(3), pp. 243–277. doi: 10.1504/IJDE.2008.023764.

Osborn, A. (1953) *Applied Imagination: Principles and Procedures of Creative Problem-Solving*. New York: Scribner.

Pugh, S. (1991) *Total Design*. Addison-Wesley Publishers.

Pugh, S. (1996) *Creating innovative products: using total design: the living legacy of Stuart Pugh*. Edited by D. Clausing and R. Andrade. Addison-Wesley Publishers.

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*. Rome, pp. 373–382.

Saaty, T. (1980) *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. McGraw-Hill.

Salonen, M. and Perttula, M. (2005) ‘Utilization of Concept Selection Methods: A Survey of Finnish Industry’, in *17th International Conference on Design Theory and Methodology*. ASME, pp. 527–535. doi: 10.1115/DETC2005-85047.

Sharif Ullah, A. M. M. *et al.* (2016) ‘Integrating CAD, TRIZ, and customer needs’, *International Journal of Automation Technology*, 10(2), pp. 132–143. doi: 10.20965/ijat.2016.p0132.

Sheu, D. D. and Hou, C. T. (2013) ‘TRIZ-based trimming for process-machine improvements: Slit-valve innovative redesign’, *Computers and Industrial Engineering*. Elsevier Ltd, 66(3), pp. 555–556. doi: 10.1016/j.cie.2013.02.006.

Sickafus, E. (1997) *Unified Structured Inventive Thinking: How to Invent*. NTELLECK, PO Box 193, Grosse Ile,MI 48138 USA.

SolidWorks - Design Methods (Bottom-up and Top-down Design) (2013). Available at: http://help.solidworks.com/2013/English/solidworks/sldworks/c_Design_Methods.htm (Accessed: 5 August 2018).

SolidWorks Conceptual Design (2018). Available at: https://www.solidworks.com/sw/docs/SWK_ConceptualDesign.pdf.

Spreafico, C. and Russo, D. (2016) ‘TRIZ Industrial Case Studies: A Critical Survey’, *Procedia CIRP*. Elsevier B.V., 39, pp. 51–56. doi: 10.1016/j.procir.2016.01.165.

Suh, N. (1990) *The Principles of Design*. New York: Oxford University Press.

System engineering fundamentals (2001). Available at: https://ocw.mit.edu/courses/aeronautics-and-astronautics/16-885j-aircraft-systems-engineering-fall-2005/readings/sefguide_01_01.pdf.

Ullman, D. (2010) *The mechanical design process 4th edition*. McGraw-Hill.

Wits, W. W., Bakker, H. M. and Chechurin, L. S. (2012) ‘Towards multidisciplinary support tools for innovation tasks’, *Procedia CIRP*, 2, pp. 16–21.

Yoji, A. (1994) *Development History of Quality Function Deployment. The Customer Driven Approach to Quality Planning and Deployment.* Tokyo: Asian Productivity Organization.

Zwicky, F. and Wilson, A. (1967) ‘New Methods of Thought and Procedure.’, in *Contributions to the Symposium on Methodologies*. Springer-Verlag. Available at: http://www.swemorph.com/pdf/new-methods.pdf (Accessed: 5 August 2018).

Publication I

Efimov-Soini, N. and Chechurin, L.
Method of Ranking in the Function Model.

Reprinted from
Procedia CIRP,
vol. 39, pp. 22-26, 2015

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 39 (2016) 22 – 26

www.elsevier.com/locate/procedia

TFC 2015 – TRIZ FUTURE 2015

Method of ranking in the function model

Nikolai K. Efimov-Soini *, Leonid S. Chechurin

Lappeenranta University of Technology, Skinnarilankatu 34, Lappeenranta 53851, Finland

* Corresponding author. *E-mail address: spb2010@mail.ru*

Abstract

At present function analysis is often used for system analysis and concept design development. Function analysis is based on modelling technique and rules of model modification, the most known of which is trimming. Trimming operator suggests system simplifications after each element of it is given a rank. . Thus, the core of the trimming is the evaluation criterion.

The article compares two known ranking methods (Gen3 method and method of Miao Li) and suggests a new method of ranking of elements in the function model. Exemplary mechanical system design analysis shows how different ranking approaches influence the trimming procedure. The method can be used for CAD/CAM software at the stage of conceptual design for automatic and semi-automatic system simplification.

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

Keywords: TRIZ, function model, ranking, function analisys,

1. Introduction

Methods for systematic conceptual design have always been in the focus of research especially since the whole design became software-frameworked. Obviously, systematic approach means certain formalism of analysis based on modelling and model transformation formalism. One of the most reasonable modelling techniques (neither based on powerful but complicated mathematical nor simple but unformal natural language models) is known to be function modelling [1]. In fact, the usage of function models enables “top-down” and “bottom-top” design style. On the other side, there are CAD system development trends to use TRIZ elements in them, or there are works with the 3D solid body models using TRIZ [2].

Currently there has been some progress in the area automated design tools development. The focus is algorithms and tool for systematic design ideas generation, troubleshooting, design transformation and simplification etc.

For example, GoldFire™ software by Invention Machine presents tool to patent design around from [3]. The product supports functional modeling performed by user or even partially automated manner from the text of the patent or another technical document, then the user performs ranking and the software suggests the elements for trimming. We should notice that big data or more precisely literature based discovery studies attack similar but slightly more general problem. They focus on extraction the concept (e.g. contents, ontology, hierarchy, interactions, subject-object action triples, cause-effect relationships, function model) from the textual data.

Another idea to automate the function model design was to use CAD environment, which is standard interface for system data processing in engineering world. The study [2, 4, 5, 6] presents an approach and working prototype of software that automates the function model extraction from 3D SolidWorks CAD assembly, and assist further function ranking and trimming.

It is quite possible that the progress in the field will deliver algorithms that are able to design function model (knowledge) of an engineering system from patents, pictures, texts etc. (information). Similar revolution was brought by powerful computers in 90s, when the design of certain types of mathematical models became almost automated due to blending of finite-element approach with graphical system description.

Peer-review under responsibility of Scientific committee of Triz Future Conference
doi:10.1016/j.procir.2016.01.160

The goal of the function modelling is to analyze the product we are going to improve. At present, there are great number of methods for assessing the function model such as the solving complexity factor [7], the value engineering [8] etc. All these methods share a common trait to focus on the product model with selected elements only.

There are three steps to design the functional model of a system [9]: the component analysis, the interaction analysis, the function analysis. Having designed the function model we can systematically derive models for simplified design by trimming.

Let us consider the function ranking and the trimming in detail. 3 (“A, B, C”) or 6 (“A, X, B, C, D, E”) rules are often used for the trimming [10]. It should be noted that these usage is directly related to the rank of the functions. The element with the lowest rank is the first candidate for trimming. The application of the formalized approach simplifies “manual” trimming procedure applications and may serve as the basis for design automation.

2. Description of methods

2.1. Definitions

We are going to use the following definitions throughout the paper.

- The rank is defined by the ranking factor. The more ranking factor has the higher the rank.
- The more useful (or more used) functions (elements) obtain the higher rank, the useless (or unused) functions (elements) obtain the lower rank.
- The rank is evaluated by integers from 1 to ∞, where the function with the highest rank obtains the value 1. So, the higher number has the lower rank.

2.2. Classical method of ranking

This method is widely used for systematic inventing [11, 12, 13].

The higher rank belongs to the functions that are closer to the key function in this method. So, we choose the furthest from the target functions as the candidates for trimming. For example, tooth brash bristles are of the highest rank, but the rubber cover on the handle is the lowest rank. Thus, the method may lead to the situation when the highest rank belong to an element that is geometrically close the target but does not perform any special function. For example, a sheet of paper laying on the chair would have the highest rank while adding nothing to main function of the system “to hold”.

2.3. Linear convolution (Method of Miao Li).

To evaluate the Function level points (ranking factor) of each component in this method Miao Li [14] introduces the function level score. For example: Useful function (5 point), Harmful function (−5 point), insufficient function (3 point), Excessive function (−3 point). Besides, the importance factor of each function level can be assigned based on expert’s opinion and practical situation.

If one component performs 3 useful functions, 1 harmful function and 2 insufficient functions to other components, and the importance factor of each function level are all equal to 1. Therefore, the component function level points is 16 points ($3 * 5 * 1 - 1 * 5 * 1 + 2 * 3 * 1$). Let us assume the total cost of the system is equal to 100, the cost ratio of this component is 10%. So the component relative cost gets 10. At last, by evaluating each component functionality points (function performance level points over relative cost), the total function rank of the engineering system components can be obtained. The higher score indicates that the component has more functionality. The lower score means that the component has not so much functionality, which gives a higher priority for Trimming.

Interestingly, the author prefers using rules A, B, C for the trimming instead of this method [14].

2.4. New method

The above methods have a significant drawback – they are not able to highlight useful elements. Thus we suggest the following approach for ranking.

- The closer function is to the target function, the higher is its rank (as the classical method of ranking – 2.2).
- The more connections, associating the element with the function, the higher rank each function has.
- Duplicate functions obtain the lower rank (for example, 2 nails are holding one board, the function "hold" of each nail has the lower rank).
- The farther element is from the key element (geometrically) the lower rate it has.

3. Case study

As an example, let us consider the concept, designed to verify the modes of polishing in the TERMOTRONIC firm (St. Petersburg, Russia) [15]. The aim of the development was to check what regimes were the best for polishing of the flowmeter “Piterflow RS” electrodes. This device was not used for industrial electrode polishing, but only to verify the modes of polishing such as the speed handle, the composition of abrasives, the processing time, etc.

3.1. Device description

This design of this device was inspired by contact lens polishing system [16, 17].

The device comprises two main systems – a rotation system, and a swing system. We have treated only the swing system by the trimming. The rotation system consists of a spindle (for a hold electrode) and an electric motor rotating a spindle.

The swing system design is presented in the figure 1. The main swing system function is to move the mount that sets in motion the pillow with abrasive, polishing the head of the electrode.

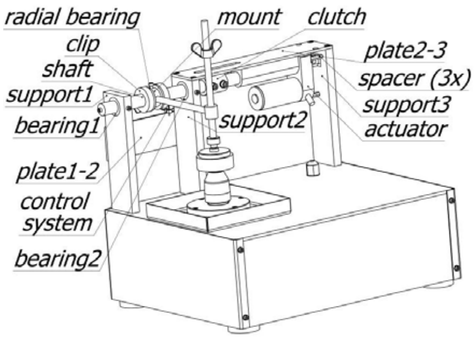


Figure 1 - Polishing device

3.2. Creation of the function model and the function ranking

The function model is shown in the figure 2. Ranking results for three different methods are presented in the tables 1-3.

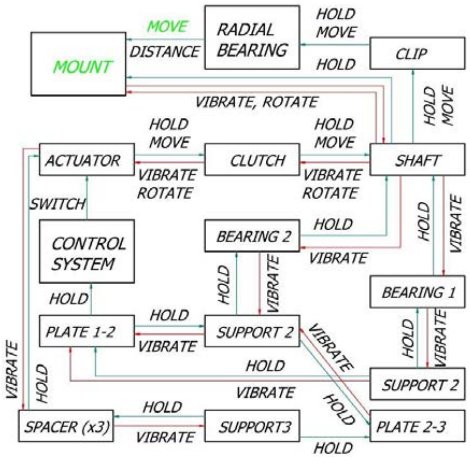


Figure 2 – Function model

Table 1. Classical method of ranking

Rank	Element 1	function	Element2
1	radial bearing	distance	mount
	shaft	hold	mount
2	clutch	hold	shaft
	clutch	move	shaft
	bearing1	hold	shaft
	bearing2	hold	shaft
	shaft	hold	radial bearing
	clip	hold	radial bearing
	clip	move	radial bearing
3	support1	hold	bearing1
	support2	hold	bearing2
	actuator	hold	clutch
	actuator	move	clutch
	shaft	hold	clip
	shaft	move	clip
4	support2	hold	plate 2-3
	spacer(x3)	hold	actuator
	control system	switch	actuator
5	support3	hold	plate 2-3
	support3	hold	spacer(x3)
	plate 1-2	hold	control system
6	support1	hold	plate 1-2
	support2	hold	plate 1-2

Table 2. Linear convolution

Rank	Element	Ranking factor
1	radial bearing	15
2	clip	10
	support3	10
3	shaft	5
	support1	5
	support2	5
	plate 1-2	5
	control system	5
4	clutch	0
	bearing1	0
	bearing2	0
	plate 2-3	0
	spacer(x3)	0
	actuator	0

Table 3. Author's method

Rank	Element 1	function	Element2	Ranking factor
1	shaft	hold	mount	-3
2	shaft	hold	radial bearing	-2
3	radial bearing	distance	mount	-1A
4	shaft	hold	clip	-1B
	shaft	move	clip	-1B
5	support2	hold	bearing2	0A
6	clutch	move	shaft	0B
7	actuator	hold	clutch	0C
	actuator	move	clutch	0C
8	clip	hold	radial bearing	2A
9	support1	hold	bearing1	2B
10	clutch	hold	shaft	3A
11	support2	hold	plate 2-3	3B
12	control system	switch	actuator	3C
13	spacer(x3)	hold	actuator	3D
14	bearing1	hold	shaft	4A
	bearing2	hold	shaft	4A
15	plate 1-2	hold	control system	4B
16	support2	hold	plate 1-2	5A
15	support3	hold	spacer(x3)	5B
16	support3	hold	plate 2-3	5C
17	support1	hold	plate 1-2	7

For this method we use the principles descripted in 2.4. For example, the function "clutch hold shaft" needs 2 steps to the target function (the initial rank equal 2) ,this one is duplicated from the functions "bearing1 hold shaft" and "bearing2 hold shaft" (2+3), and, as well, the element obtains 2 links (2+3-2=3). Also the equal factors obtain 4 other functions, but the function "clutch hold shaft" is geometrically closer to the mount (because the elements clutch and the shaft is closer to the mount) than 3 function and is farther than function "support2 hold bearing2", so this function gets a high rank (B).

3.3. Ranking results

In fact the classical method of ranking gives the higher rank to the functions that are the nearest to the target element. For the system we analyze it means the radial bearing (table 1) which is intermediary only. There are the most useless element in the device, in opposite the author's method "highlights" the most used component. he most useless elements (support1, support2, support3) are defined identically in both methods at the same time. The "useful" element in the linear convolution method (table 2) is same as in the classical method - radial bearing one, but the "useless" element is different. It means that the method is not suitable for the ranking in concepts, but in theory this method "highlights" the most "useless" (but maybe not unused) component, what is very important for the patent design around (tables 1-3).

4. Conclusions

The paper discusses design complexity reduction algorithms based on function modelling technique. Difference in tow known element ranking methods are highlighted and a new approach is suggested. More precisely,

- The classical method of ranking is simple for awareness and understanding, it does not require the specification of carrying out any further calculations, and can be used as a method of rapid assessment, but for the evaluation in the automatic mode, requires the supplementation.
- The linear convolution method highlights the most unused or useless item, which is theoretically the easiest to be removed, which is convenient to the patent design around.
- The new method as an "upgrade" to the Classical method of ranking, to adapt it to the conduction of the automated trimming.

5. Further development

The further development goes in 2 areas: development (and check) the formal mechanism for the trimming after choosing the concept (in the new development) and the development mechanism for automatic and semi-automatic trimming.

6. Acknowledgments

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

References

[1] V. Gerasimov, V. Kalish, A. Kuzmin, and S. S. Litvin, Basics of Function-Cost Analysis approach. Guidlines (in Russian). Moscow: Moscow, Inform-FSA, 1991, p. 40.

[2] Introducing trimming and function ranking to SolidWorks based on function analysis. Chechurin, Leonid S. Wits, Wessel W. Bakker, Hans M. Vaneker, Tom H.J. Proceedings of Triz Future Conference 2011. 2011. pp. 215-225

[3] https://www.ihs.com/products/design-standards-software-goldfire.html Last visit 2015/06/08[16]

[4] Towards multidisciplinary support tools for innovation tasks. W.W. Wits,*, H.M. Bakker, L.S. Chechurin 1st CIRP Global Web Conference: Interdisciplinary Research in Production Engineering. 2012. 9 pages.

[5] Integrating TRIZ function modeling in CAD software. Bakker, Hans M. Chechurin, Leonid S. Wits, Wessel W. Proceedings of TRIZfest-2011. 2011. 18 pages.

[6] Towards multidisciplinary support tools for innovation tasks. W.W. Wits,*, H.M. Bakker, L.S. Chechurin. 1st CIRP Global Web Conference: Interdisciplinary Research in Production Engineering. 2012. 9 pages.

[7] Creating innovative products : using total design : the living legacy of Stuart Pugh / Stuart Pugh. edited by Don Clausing, Ron Andrade. Addison-Wesley, 1996. 544 p. ISBN: 0-201-63485-6

[8] Extended Model for Integrated Value Engineering. Florian G.H. Behncke, Sebastian Maisenbacher, Maik Maurer. Procedia Computer Science Volume 28, 2014, Pages 781–788.

[9] TRIZ for Engineers: Enabling Inventive Problem Solving, First Edition. Karen Gadd. 2011 John Wiley & Sons, Ltd. Published 2011 by John Wiley & Sons, Ltd. ISBN:978-0-470-74188-7 p.483

[10] TRIZ-based trimming for process-machine improvements: Slit-valve innovative redesign D. Daniel Sheu, Chun Ting Hou. Computers & Industrial Engineering 66 (2013) p.555–566

[11] Basic GEN3 Innovation Discipline (G3:ID) Training. Pages 168.

[12] Patent “Document semantic analysis/selection with knowledge creativity capability utilizing subject-action-object (SAO) structures” US 6167370 A. https://www.google.ru/patents/US6167370 Last visit 2015/06/04
[13] Patent “Computer based system for imaging and analyzing a process system and indicating values of specific design changes US 6202043 B1” https://www.google.ru/patents/US6202043 Last visit 2015/06/04
[14] A TRIZ-based Trimming method for Patent design around. Miao Li , Xinguo Ming, Lina He, Maokuan Zheng, Zhitao Xu. Computer-Aided Design 62 (2015) pp 20–30.
[15] http://termotronic.ru Last visit 2015/05/20.
[16] http://www.sciencechannel.com/tv-shows/how-its-made/videos/how-its-made-contact-lenses/ Last visit 2015/05/20.
[17] Patent “Contact lens polishing system US 3782045 A” https://www.google.ru/patents/US3782045?dq=contact+lenses+polishing+machine&hl=ru&sa=X&ei=jh9cVb6XJIH7ywPM7YGYDA&ved=0CBwQ6AEwAA Last visit 2015/05/20

Publication II

Efimov-Soini, N. and Uzhegov, N.
The TRIZ-based tool for the electrical machine development.

Reprinted from
Proceedings of a conference Progress In Electromagnetics Research Symposium - Spring (PIERS)
pp. 1396-1403, 2017
Open publication

2017 Progress In Electromagnetics Research Symposium — Spring (PIERS), St Petersburg, Russia, 22–25 May

The TRIZ-based Tool for the Electrical Machine Development

N. Efimov-Soini[1] **and N. Uzhegov**[2]

[1]Lappeenranta University of Technology, Finland
[2]SpinDrive, Finland

Abstract— This paper is devoted to the electrical machine design development by using the TRIZ-based tool. The implemented approach is based on the TRIZ tool called the function analysis. This tool is used as a formal method for the electrical machine improvement and design development. It takes into account the system structure and relations between the system elements. The presented method is applied for a case study and illustrates the transition from conventional machines to high-speed electrical ones.

1. INTRODUCTION

The conceptual design stage is one of the most important stages in the product life-cycle According to Ullman about 70% of a product cost is the conceptual design stage result [1]. It is very important to use this stage to select the best concept. For this purpose inventive design methods are very effective. There are different inventive methods, for example, TRIZ [2], Axiomatic Design [3] and USIT [4] to name a few.

TRIZ (Russian acronym "Teoriya Reshenia Izobretatelskih Zadach" — the Theory of the Inventive Problem Solving) is a powerful tool for the design development and improvement. TRIZ was developed in 1950th by the Soviet inventor Genrih Altshuller [2]. Different TRIZ tools are used in industry and science [5–8].

One of the TRIZ tools is the function analysis [9]. It is used for the design development and improvement for the static and dynamic systems [10]. In this paper the function analysis method is used for the rotating electrical machine development.

In this paper the usage of the inventive TRIZ tool allows obtaining a new concept pattern for the electrical machine development. The function approach is possible to use for the design, because information on the conceptual design stage is uncertain and each design iteration is very expensive. The implementation of the TRIZ tool allows obtaining the result in the cost-effective way The presented method consists of the four main steps: the component analysis, the interaction analysis, the function modeling and the trimming. During the first step the system is decomposed to the elements. On the second step relations between the elements are defined. On the third one each relation is defined as a function and the each function importance is defined as well. Finally, the trimming of the elements is performed to improve the system.

There are several types of the function modeling methods [11]. The Functional Flow Block Diagram (FFBD), used in the system engineering [12], is some of them. This is a function-oriented approach based on the sequential relationship of all functions in the system. FFBD is developed from the top to the bottom and it proposes the hierarchal view of the functions across the series of levels Aim of each one is to identify a single task on a higher level by means of the functional decomposition Compared with FFBD, the Functional Analysis System Technique (FAST) diagram focuses on functions of the product rather than its specific design In this method the system is presented in a tree structure where each function is presented in a verb + noun format.

In contrast to FFBD and FAST, TRIZ function modeling takes into account the physical interaction between the system elements and type of this interaction. For example is it useful, harmful, insufficient or excessive. In this approach the system is presented by using the component and function views together. Therefore, it is possible to create a new design pattern and make a new design based on the initial design.

The growing number of applications where electrical machines are used is leading to the situation, when rotating electrical machines are one of the major electricity consumers. The high system efficiency of these applications is necessary to reduce global greenhouse gas emissions. Therefore, it is very important to apply the best suitable electrical machine type for every application [13]. In this paper the function analysis method demonstrates how the transition from the conventional electrical machine to the high-speed electrical machine can optimize the system design.

This paper is structured as follows: Section 2 introduces the state of the art, Section 3 describes the design method, in Section 4 the case study is presented and Section 5 is devoted to the conclusions.

2. THE STATE OF THE ART

2.1. TRIZ in Industry and Science

TRIZ is a set of powerful tools used in different areas of industry and science. The most frequently used approaches are forty inventive principles, Ideal Final Result (IFR) and function analysis [14]. These methods are used in various science and industry fields. Forty inventive principles and Ideal Final result are good inventive tools to create a new design or improve it, but these methods are very uncertain and creative. In contrast function analysis is very formal method based on the exact steps. This method is used for the design development, the system improvement and the patent-around design.

2.2. The TRIZ Function Analysis

The function analysis in its TRIZ-related form appeared already in 1991 and was originally targeted at the engineering system analysis [15]. There are different approaches in the TRIZ function analysis. The literature review has shown that presented TRIZ-based tools have some disadvantages. For example, Li's method doesn't take into account the system dynamization [16]. The GEN3 method's key disadvantage is a high importance of the elements that do not have an important function, but are close to the key function element or elements — "mediators" [9]. The method, presented in this paper, takes into account links between the system elements, their importance and the system dynamization.

2.3. Electrical Machines

Rotating electrical machines produce above 90% and consume more than 40% of the worldwide electrical energy [17]. The global CO_2 emission reduction is only possible if this huge amount of energy will be produced and consumed efficiently. Therefore, it is important to design, produce and install highly efficient electrical machines. Political decisions support the adaptation of the highly efficient machines by issuing the new regulations. For example, 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) has accepted an extension to the Kyoto protocol in December 2015. This agreement will allow keeping global warming below 1.5–2°C.

The recent trends in the electrical machine design, which allows achieving high system efficiency include novel machine topologies, new materials and efficient manufacturing [18]. An appropriate selection of a suitable machine topology for the exact application can significantly increase the total system efficiency and reduce the greenhouse gas emissions. The function analysis provides an opportunity to select a suitable machine topology on the very early design stage and to reduce the initial design time.

3. THE METHOD DESCRIPTION

The presented method consists of four main steps: the component analysis, the interaction analysis, the function modeling and the trimming. This method is based on the GEN3 function analysis and trimming [9], however few new ideas are proposed.

3.1. The Component Analysis

This step consists of the system decomposition into the elements The following algorithm is proposed for the decomposition:

a) The system is decomposed to the main elements, usually to a big assembly. For example, a car consists of a body, an electric system, an engine etc..

b) The system target element is selected.

c) Decomposed elements are divided into the smaller components. The assembly is divided into the subassembly; the subassembly is divided into parts etc. The main goal of this step is to create a detailed system decomposition model in the area close to the target element.

d) Finally the interaction analysis, the function modeling and the trimming are held according to the algorithm presented in Subections 3.2–3.4. If the result is not satisfactory, then the system is additionally decomposed (step c).

The presented method is based on the algorithm for meshing in the finite element analysis [19].

3.2. The Interaction Analysis

On this step an interaction between the elements is defined. For illustration a simple system, which consists of the frame, the stator core and the windings is illustrated. The frame interacts with stator core and doesn't interact with the windings; on the other hand windings interact with the core and don't do it with the frame.

3.3. The Function Modeling

In this step, a type of the interaction between the elements is defined as a function. The function rank of each one is defined in accordance with its importance The following definitions are used throughout the paper:

- The rank is defined by the ranking factor. The lower ranking factor, the higher the rank.
- The more useful (or more used) functions or elements obtain the higher rank; the useless (or unused) functions or elements obtain the lower rank.
- The rank is evaluated by integers from 1 to ∞, where the function with the highest rank obtains the value 1. Hence, the higher number has the lower rank.
- For function with the equal ranking fact or a distance between the element associated with the function and the target element is additionally taken into account. These ranking factors are marked with letters A, B, C etc., where letter A indicates a function with the smallest distance to the target element. Therefore, the rank for the function with the letter A is higher than for the function with the letter B.
- The target function obtains the initial rank 0.

The ranking is based on the ranking system presented in [9, 10]. In this method, the function ranking is based on the function importance but also on the number of relations among function elements. The main definitions of the presented approach are the following:

- The closer the function to the target function, the higher its rank. This step is similar to GEN3 ranking method.
- The element with the highest number of connections is the most important for the system. All functions, associated with this element, have the high rank.
- The duplicated functions obtain the lower rank For example, if two bolts are holding one stator end plate, the function "hold" of each bolt has the lower rank.
- The farther element from the key element geometrically, the lower rank it has.

3.4. The Trimming

Three following formal rules [9] are used for trimming:

a) The function carrier can be trimmed if the object of the function is trimmed.
b) The function carrier can be trimmed if the object of the function can perform the useful function by itself.
c) The function carrier can be trimmed if another function carrier performs its useful function.

4. THE CASE STUDY

The case study is focused on the electrical machine development for the applications that require the high rotational speed The areas, where high rotational speed increases efficiency of the working process include heating, ventilation and air conditioning (HVAC), waste heat recovery systems (WHRS), oil and gas compressors, distributed energy generation and spindle drives to name a few.

A common way to increase the rotational speed is to install a gearbox between the conventional electrical machine and the process working tool. Figure 1 shows the computer-aided design (CAD) model of the system. The whole drivetrain consists of the frequency converter, conventional electrical machine, gearbox, and working tool. The frequency converter feeds the machine from the network. It provides control of the rotational speed, slip, and voltage level. The induction motor transforms the electrical energy to the mechanical one. It consists of several key components. The frame holds the whole structure. The stator consists of the laminated core and insulated windings. The windings and core create the rotational electromagnetic field. Bearings are supporting the rotor. The induction machine rotor consists of the laminated core and the squirrel cage from the highly conducting material. The rotor is connected to the gearbox, that in case of a high-speed application gears up the rotational speed. Finally, the gearbox is connected to the working tool.

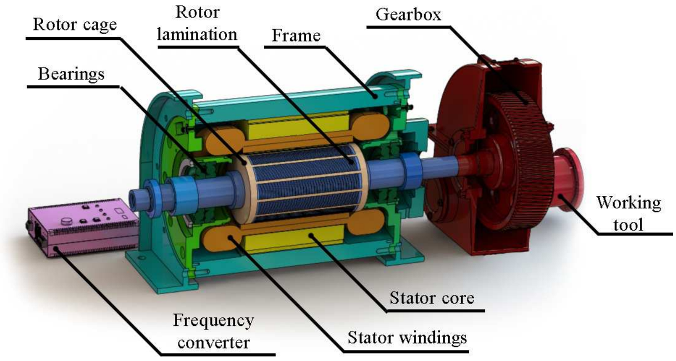


Figure 1. Conventional induction machine with a gearbox.

4.1. The Case Study Component and Interaction Analysis

First, the conventional drivetrain with the induction machine is decomposed into 10 elements, such as the working tool gearbox, bearing, rotor lamination, rotor cage, magnetic field, stator core, stator windings, frequency convertor and frame. The presented decomposition consists of the machine elements, magnetic field and environment, that is represented by the working tool. The interactions between the elements are listed in Table 1.

Table 1. Interactions in the conventional electrical machine.

	Working tool	Gearbox	Bearings	Rotor lamination	Rotor cage	Magnetic field	Stator core	Stator windings	Frequency converter	Frame
Working tool	■	+	-	-	-	-	-	-	-	-
Gearbox	+	■	-	+	-	-	-	-	-	-
Bearings	-	-	■	+	-	-	-	-	-	-
Rotor lamination	-	+	+	■	+	-	-	-	-	-
Rotor core	-	-	-	+	■	+	-	-	-	-
Magnetic field	-	-	-	-	+	■	-	+	-	-
Stator core	-	-	-	-	-	-	■	+	-	+
Stator windings	-	-	-	-	-	+	+	■	+	-
Frequency converter	-	-	-	-	-	-	-	+	■	+
Frame	-	-	-	-	-	-	+	-	+	■

4.2. The Case Study Function Modeling

After the interaction analysis each link is defined as a function. In the case study the following key functions are defined: the gearbox rotates the working tool, the rotor lamination rotates the gearbox, bearings hold the rotor, the rotor lamination holds a rotor cage, the magnetic field rotates the rotor cage, the stator core and windings create the magnetic field, the stator core holds stator windings, the frequency converter controls stator windings and the frame holds the stator core. These and some other functions are mapped in the function model and shown in Figure 2. In this representation some functions and processes in the electrical machine are simplified to illustrate the key idea of the method.

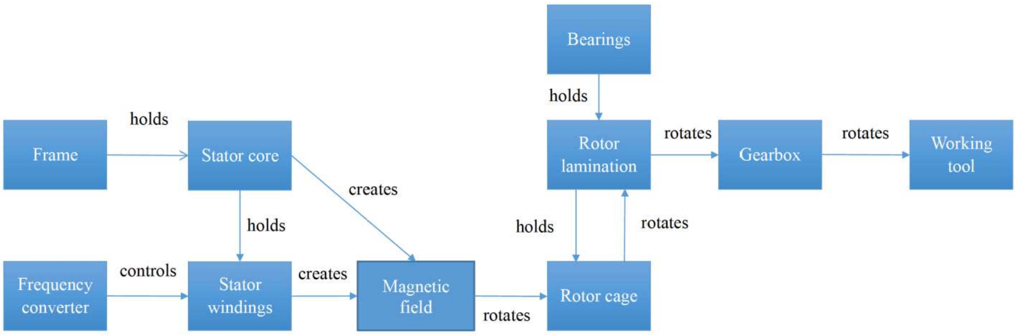


Figure 2. Function model of the conventional drivetrain.

The ranking factor and each function's rank are defined by using the function modeling rules from Subsection 3.3 and function model in Figure 2. For this purpose the distance between elements is decreased by numbers of links. Further, the rank is scored by following the principle "the lower ranking factor, the higher the rank"

Two functions — "gearbox rotates working tool" and "rotor lamination holds rotor cage" are considered to illustrate an example The first one has zero distance to the working tool, and the second function has the distance two because there are two functions between the rotor lamination and the working tool. These functions are "rotor lamination rotates gearbox" and "gearbox rotates working tool". In the function "gearbox rotates working tool" element "gearbox" has two links. One with the rotor lamination and another with the working tool. The element "rotor lamination" has four links. Two links are with the rotor cage, one with the gearbox and one with the bearings. None of these functions are duplicated in this example. According to the ranking rules in Subsection 3.3 the ranking factor for the function "gearbox rotates working tool" is equal to -2. This is because the distance is 0, there are two links and the functions are not duplicated $(0 - 2 + 0 = -2)$. For the function "rotor lamination holds rotor cage" the ranking factor is also -2. The distance is 2, there are four links and the functions are not duplicated $(2 - 4 + 0 = -2)$. For the final ranking geometric rule is used. The function "gearbox rotates working tool" is closer to working tool than the function "rotor lamination holds rotor cage". Therefore, the first function gets the letter "A" and the second gets the letter "B". In addition, the functions "rotor lamination rotates the gearbox" and "rotor cage rotates the rotor lamination" have the ranking factors -3 and -1 accordingly. It means that the considered functions receive the rank 2. The final rank for the function "gearbox rotates working tool" is "2A" and for the function "rotor lamination holds rotor cage" the rank is "2B".

The calculations are similar for other functions. The results of the ranking process are presented in Table 2.

Finally, the ranking trimming rules from Subsection 3.4 are used for the system improvement The formal trimming rules are applied for all functions starting with the lowest rank. When function is trimmed, process stops.

For example, the function "frame holds stator core" isn't trimmed because the object of the function "stator core" isn't trimmed; this function can't perform the useful function by itself and another function carrier doesn't perform its useful function. Similar analysis is performed for other functions The function "gearbox rotates working tool" can be trimmed if the gearbox is trimmed. Another function carrier may perform its useful function This function is transferred to the element "rotor" and is transformed to the function "rotor rotates working tool". The improved function model is illustrated in Figure 3. Some elements of the system have been adjusted.

Figure 4 shows the drivetrain that implements the improved function model, presented in Figure 3. A new system is a high-speed induction machine. Due to the challenges of the high-speed operation some changes are required in this machine design. The frequency converter and frame require minor changes. For example, more advanced control techniques can be used in the converter to control the rotation. The stator lamination must be selected thinner and with lower per unit losses to minimize the core losses due to the high supply frequency. Special types of windings and

Table 2. The ranking results.

Function	**Distance**	**Links**	**Ranking Factor**	**Rank**
Gearbox rotates working tool	0	2	−2	2A
Rotor lamination rotates gearbox	1	4	−3	1
Bearings hold rotor lamination	2	1	1	5A
Rotor lamination holds rotor cage	2	4	−2	2B
Rotor cage rotates rotor lamination	2	3	−1	3
Magnetic field rotates rotor cage	3	3	0	4
Stator core creates magnetic field	4	3	1	5B
Stator windings create magnetic field	4	3	1	5B
Stator core holds stator windings	5	3	2	6
Frequency converter controls stator windings	6	1	5	7B
Frame holds stator core	6	1	5	7A

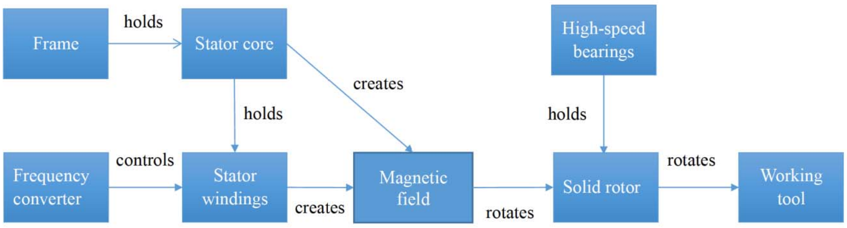


Figure 3. The function model of the improved system.

their arrangement must be selected to avoid extra copper losses. Bearings and the rotor part require the redesign because they need to tolerate higher mechanical stresses. Special types of bearings are used in high-speed machines, for example, ceramic ball bearings, Active Magnetic Bearings (AMB), or air-foil bearings [20]. In the case of AMB and air-foil bearings additional back-up bearings are required. They act as the safety damper in case of the rotor dropdown. The rotor structure is modified in way that instead of the laminated rotor the solid rotor is selected. Such construction allows achieving very high peripheral speeds up to 400 m/s. The solid rotor additional slits are drilled in the rotor to increase electromagnetic performance.

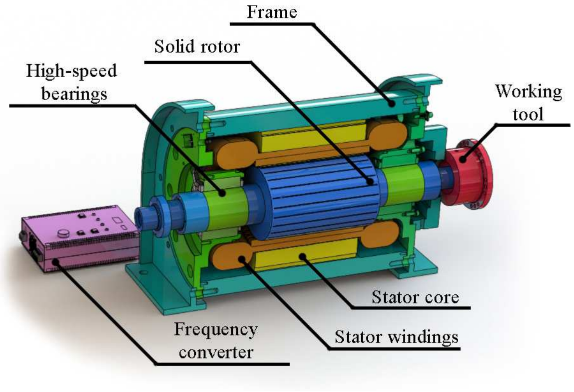


Figure 4. High-speed induction machine model.

The key benefits of the high-speed machines are higher system efficiency, lower size and footprint, higher power density, and wide operational range and high partial load efficiency. This example demonstrates that an implementation of the function analysis can provide the guidelines for the electrical machine type selection significantly reduce the number of iterations, reduce the design time and the number of errors at the concept design stage.

5. CONCLUSIONS

In this paper the method of the system development and improvement is presented with the example of the electrical machine. The major steps and the procedures are explained in details. As a result the function analysis method enables to develop a new design pattern. This approach is formal, easy to use in various design fields and to automate.

The proposed method is an attempt to transform the design inventive process into the formal algorithm. This method is one of the ways to improve the conceptual design procedure by selecting the suitable electrical machine type in the very beginning of the design process The further development is possible by using the presented approach in connection with CAD model in a semi-automatic or an automatic mode.

REFERENCES

1. Ullman, D., *The Mechanical Design Process*, 4th Edition, McGraw-Hill, 2010.
2. Altshuller, G., *Creativity as an Exact Science*, Gordon And Breach, New York, 1984.
3. Suh, N., *The Principles of Design*, Oxford University Press, New York, 1990.
4. Sickafus, E., *Unified Structured Inventive Thinking: How to Invent*, NTELLECK, P.O. Box 193, Grosse Ile, MI 48138 USA, 1997.
5. Gironimo, G. Di, D. Carfora, G. Esposito, C. Labate, R. Mozzillo, F. Renno, A. Lanzotti, and M. Siuko, "Improving concept design of divertor support system for FAST tokamak using TRIZ theory and AHP approach," *Fusion Eng. Des.*, Vol. 88, 3014–3020, 2013.
6. Albers, A., D. Wagner, L. Kern, and T. Höfler, "Adaption of the triz method to the development of electric energy storage systems," *Proc. CIRP*, Vol. 21, 509–514, 2014.
7. Jupp, M. L., I. F. Campean, and J. Travcenko, "Application of TRIZ to develop an in-service diagnostic system for a synchronous belt transmission for automotive application," *Proc. CIRP*, Vol. 11, 114–119, 2013.
8. Chechurin, L., "TRIZ in Science. Reviewing indexed publications," *Procedia CIRP*, Vol. 39, 156–165, 2016.
9. Ikovenko, S., S. Litvin, and A. Lyubomirskiy, *Basic Training Course*, GEN3 Partners, Boston, 2005.
10. Efimov-Soini, N. K. and L. S. Chechurin, "Method of ranking in the function model," *Proc. CIRP*, Vol. 39, 22–26, 2016.
11. Cooke, J., "TRIZ-based modelling and value analysis of products as processes," *Proceedings of Trizfuture*, 1–11, Sept. 2015.
12. Akiyama, K., *Function Analysis: Systematic Improvement of Quality and Performance*, Productivity Press Inc., Cambridge MA, 1991.
13. Uzhegov, N., N. Efimov-Soini, and J. Pyrhönen, "Assessment of materials for high-speed PMSMs having a tooth-coil topology," *Progress In Electromagnetics Research M*, Vol. 51, 101–111, 2016.
14. Ilevbare, I. M., D. Probert, and R. Phaal, "A review of TRIZ, and its benefits and challenges in practice," *Technovation*, Vol. 33, 30–37, 2013.
15. Gerasimov, V., V. Kalish, A. Kuzmin, and S. Litvin, *Basics of Function-Cost Analysis Approach. Guidlines*, Moscow, InformFSA, 1991 (in Russian).
16. Li, M., X. Ming, L. He, M. Zheng, and Z. Xu, "A TRIZ-based trimming method for patent design around," *CAD Comput. Aided Des.*, Vol. 62, 20–30, 2015.
17. De Almeida, A. T., F. J. T. E. Ferreira, and A. Q. Duarte, "Technical and economical considerations on super high-efficiency three-phase motors," *IEEE Trans. Ind. Appl.*, Vol. 50, No. 2, 1274–1285, 2014.
18. Uzhegov, N., E. Kurvinen, and J. Pyrhönen, "Design limitations of 6-slot 2-pole high-speed permanent Magnet Synchronous machines with Tooth-Coil windings," *2014 16th European Conference on Power Electronics and Applications*, 1–7, 2014.

19. Reddy, J. N., *An Introduction to the Finite Element Method.*, 3rd Edition, McGraw-Hill, New York, 2006.
20. Uzhegov, N., E. Kurvinen, J. Nerg, J. Pyrhönen, J. T. Sopanen, and S. Shirinskii, "Multidisciplinary design process of a 6-slot 2-pole high-speed permanent-magnet synchronous machine," *IEEE Trans. Ind. Electron.*, Vol. 63, No. 2, 784–795, Feb. 2016.

Publication III

Efimov-Soini, N. and Chechurin, L.
The Method of CAD Software and TRIZ Collaboration.

Reprinted with permission from
Communications in Computer and Information Science
Vol. 754, pp. 517-527, 2017

The Method of CAD Software and TRIZ Collaboration

Nikolai Efimov-Soini(✉) and Leonid Chechurin

Lappeenranta University of Technology, Lappeenranta, Finland
nefso@mail.ru, leonid.chechurin@lut.fi

Abstract. This article is devoted to the collaboration of TRIZ function analysis and the engineering CAD software. The presented approach uses the TRIZ function modeling for the system development and improving, meanwhile, it uses the information from the CAD model in the initial source. The case study is illustrated by the industrial example. Its aim is the improving of the electromagnetic flow meter magnetic system the, created by means of the SolidWorks software. For process automatization the software, created in C# Microsoft Visual Studio by using the SolidWorks API tool. The suggested method proposes the formal mechanism based on the TRIZ methodology for the system developing and improving by means of the CAD model. This one may be used as in the conceptual design, so detail design stages and for patent-around design.

Keywords: TRIZ · CAD · Function analysis · Trimming

1 Introduction and States of the Arts

According to Ullman [1], decisions made during the design process have a great effect on the cost of the product but these decisions cost is very low. Also, about 75% of the manufacturing cost of the typical product is committed by the end of the conceptual phase process. It means that decisions, made after this time, can influence only 25% of the product's manufacturing cost. On the other hand, the Top-down approach [2] permits to create the common Computer-Aided Design (CAD) model on the conceptual design stage. In this case, inventive methods in collaboration with the CAD software may be very effective.

This paper presents the method that combines tool based on the application programming interface (API) of the SolidWorks software and the Theory of Inventive Solving (TRIZ).

The TRIZ (Russian acronym "Teoriya Reshenia Izobretatelskih Zadach" – the Theory of the Inventive Problem Solving) is an inventive method proposed by the Soviet scientist and the inventor Altshuler (1926–1998) in 1956 [3]. He studied about 40000 patents and drew out the formal processes for some new ideas of the generation and the technical evolution trends. Such methods are 40 inventive principles, contradictions, ideality, and patterns of the evolution. In presence, TRIZ is widely used in different areas of industry and science [4–7].

The functional part of the method is based on TRIZ function analysis. There are several types of the function presentation of the system, such as the Functional Flow

A. Kravets et al. (Eds.): CIT&DS 2017, CCIS 754, pp. 517–527, 2017.
DOI: 10.1007/978-3-319-65551-2_38

Block Diagram (FFBD) [8], the Functional Analysis System Technique (FAST) [9], the Integrated Computer Aided Manufacturing DEFinition for Function Modeling (IDEF0) [10], etc. All these methods use the function approach for the system presentation. For example, the FFBD is the function-oriented approach based on the sequential relationship of all system functions. FFBD develops a system from the top to the bottom and it proposes the hierarchal view of the functions across the series of levels. The aim of each one is to identify a single task on a higher level by means of the functional decomposition. Compared with FFBD, the Functional Analysis System Technique (FAST) diagram focuses on functions of the product rather than its specific design. There the system is presented in a tree structure where each function is presented in a verb + noun format.

In contrast to FFBD and FAST, the TRIZ function modeling takes into account the physical interaction between the system elements and the type of this interaction. There are four types of interaction - useful, harmful, insufficient or excessive. In this approach, the system is presented by using the component and function views together. Therefore, it is possible to create a new design pattern and make a new design based on the initial design.

This paper is devoted to two main problems such as the transferring of the CAD model to the TRIZ function model by using the API technology [11] and the Function Model improving by means of the functional analysis. These problems are solved to receive new patterns, to improve the existing design or for patent-around design.

In the area of collaboration between CAD and TRIZ, the proposed approach is not a novelty. In one hand Dr. Ullah proposed the methodology [12] of integrating CAD, TRIZ, and customer needs, but he did not propose any formal integration mechanism. On the other hand, Dr. Bakker and Dr. Chechurin [13, 14] developed the formal mechanism of the collaboration. The proposed approach evolves ideas of the last one by means of the function-oriented approach.

There are different methods for the design improvement and development, such as the topological improvement (e.g. Generative design software Autodesk Within - [15]), using CAI (Computer-Aided Invention, e.g. GoldFire [16]) also the TRIZ approach may be used. The first one proposes the topological optimization without a new design generation. The second one proposes a new design generation but without the collaboration to the CAD model. It is used in additive technologies. The CAI approach uses the function approach, but it doesn’t collaborate with the engineering software. This approach is used in the patent-around design. The TRIZ function analysis is the third in the list of the TRIZ tools popular method [17]. There are different approaches in this case. For example, Miao Li’s method [18] used in patent around design. It takes into account an each element importance. Gen3 method [19] is used for design improvement and development. This one uses the formal functional approach to rank the importance of each function in the system. Presented method combines these methods and supplements them, also collects the previous works in this domain [20–22].

The remainder of this paper is structured as follow: Sect. 2 is devoted to the method description, in Sect. 3 the method is illustrated by industrial case study – improving the electromagnetic flow meter, Sect. 4 is considered to materials conclusions and finally, Sect. 5 is devoted to the further development.

2 Method Description

The suggested method is based on [13, 14]. There are 3 main steps: the export from the CAD model, the function modeling, and the trimming. In the first step, the information from the CAD model is received. In the second step, the TRIZ function model is created by using information received above. Finally, the trimming of the TRIZ function model is used for system improving and development.

2.1 Export from CAD Model

The API tool is used for the information export from the CAD model. This one is included in the popular CAD software (SolidWorks, Inventor, SolidEdge, Kompas etc.) and permits to receive some information from the model or to work in this software by using commands “outside”. In this case, the model structure and the relationship between elements (mates in SolidWorks) are received by using the SolidWorks API. In fact, this step replaces the component analysis in [19]. The translation is completed by using the special software, created in the C# Visual Studio 2017 by using the SolidWorks API tool.

2.2 Function Analysis

The function analysis model is based on [19–21]. There are three formal steps: the component analysis, the interaction analysis, and the function modeling. The first one is devoted to the system decomposition to elements. It is completed above and is similar to [19]. The following algorithm is proposed for the decomposition:

1. The system is decomposed into the main elements, usually to a big assembly. For example, a car consists of a body, an electric system, an engine, etc.
2. User select target element in the system.
3. Decomposed elements are divided into the smaller components. The assembly is divided into the subassembly or parts; the subassembly is divided into parts, etc. The main goal of this step is to create a detailed system decomposition model in the area close to the target element of the system.
4. In the final step, the interaction analysis, the trimming is held according to the algorithm presented in Sect. 2.3. If the result is not satisfactory, then the system is additionally decomposed (step 3).

In the second step, the relation between elements is defined. For example, a simple system, which consists of the frame, the shaft, and the gear, is illustrated. The frame interacts with the shaft and doesn’t interact with the gear; on the other hand, the gear interacts with the shaft and don’t do it with the frame. In this case interaction analysis is based on mates of the CAD model, but may be modified by the user, e.g. he may add or remove elements. For example, the mate “contact” in the CAD model is equal to the function “hold” in the function model, and for bolts and nuts function “hold” is defined as the default. The final step defines the interaction between elements as a function and type of this interaction. There are four types of interaction: useful, harmful, insufficient or excessive. But in this case, one useful function is considered. Also, the function ranking is done.

Finally, the function rank defines an each function importance. It is based on the following formal rules:

1. The rank defines the functional importance. The more useful (or more used) functions obtain the higher rank; the useless (or unused) functions obtain the lower rank.
2. The function rank is defined by the ranking factor (the degree of importance). This one is a rational number and may be positive or negative.
3. The rank is evaluated by integers from 1 to ∞, where the function with the highest rank obtains the value 1. Hence, the higher number has the lower rank.
4. The target function (system main function) obtains the initial rank 0. This function is defined by the user.
5. The system is static in this case; it means that the function rank and the ranking factor are time-independent.
6. If the ranking factor for two functions is equal, the function with a smaller distance between the function carrier and the target element obtains the higher rank. In this instance rank of the function wrote in type: number + letter. For example: 2A, 3B, 7C etc.

The following formula is used for ranking factor calculation:

$$RF = IR - NL + ND + 1 \tag{1}$$

where: RF - Ranking factor, IR-Initial rank, NL - Number of links, ND - Numbers of duplicated functions.

2.3 Trimming

This step is based on formal trimming rules [23]. A function may be trimmed if:

1. An object of the Function does not exist;
2. An object of the Function performs the function itself;
3. Another Engineering System Component performs the useful function of the Function Carrier.

Where an object that performs a function is called the Function Carrier, while the object on which the function is performed is called the Object of the Function. For example in the function “hammer move nail”, the hammer is the function carrier, moves – the function, and the nail is an object of the function.

The trimming rules are applied for all function starting with the lowest rank in this case. After an each trimming iteration, the software proposes a user to continue or to finish the trim process. If the trimming is impossible, the process stops.

3 Case Study

The case study is illustrated with the electromagnetic flowmeter magnetic system improvement. The electromagnetic (EM) flow meter is used for the heating, the air conditioning, the water supply and the water treatment, in the drinking water system distribution, the pipelines etc. The main feature of the electric flow meter is its ability to work with any conductive liquid.

In the electromagnetic flowmeter, the magnetic field is generated by coil interaction with water that generates an electric signal. This signal is processed by the flow meter controller, and it displays the measured data on the screen or sends the data to the external server.

This one is presented in the Fig. 1 and consists of two nuts, the stud, the coil and the tube. The stud is welded to the tube and holds the coil in this system. Meanwhile, the coil is fixed in the stud with two nuts. The coil is used to generate the magnetic field into the tube.

3.1 Case Study Export from CAD Model

The special software is developed for information translation. This one is created in the C# Microsoft Visual Studio by using SolidWorks API tool. It permits to create the function model by using following information: the name, the type of component (assembly or part) and mates (interaction between elements). The presented tool replaces component analysis in the functional analysis. The developed software presented in the Fig. 2.

The suggested software works in a semi-automatic manner. It proposes the same ideas to a user, but one can interrupt and each step in this algorithm. On other hand, the user can optimize the software work. - The user may add changes in the process in any step (e.g. add or remove functions, elements, change the type of the relation etc.).

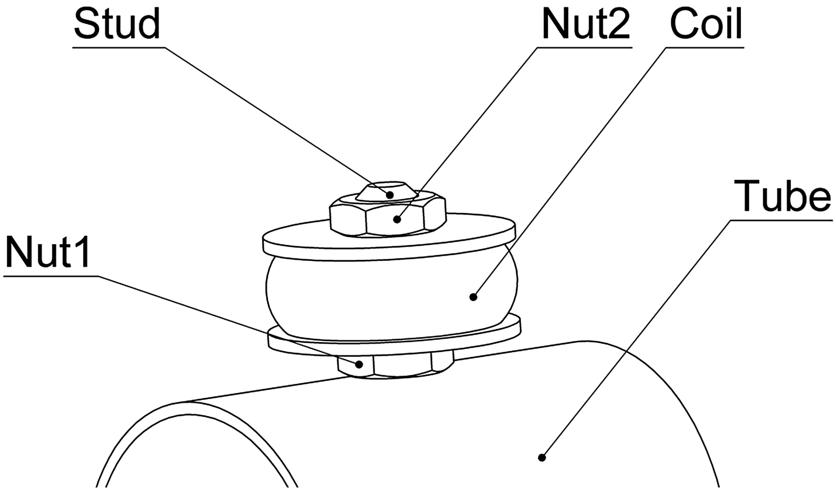
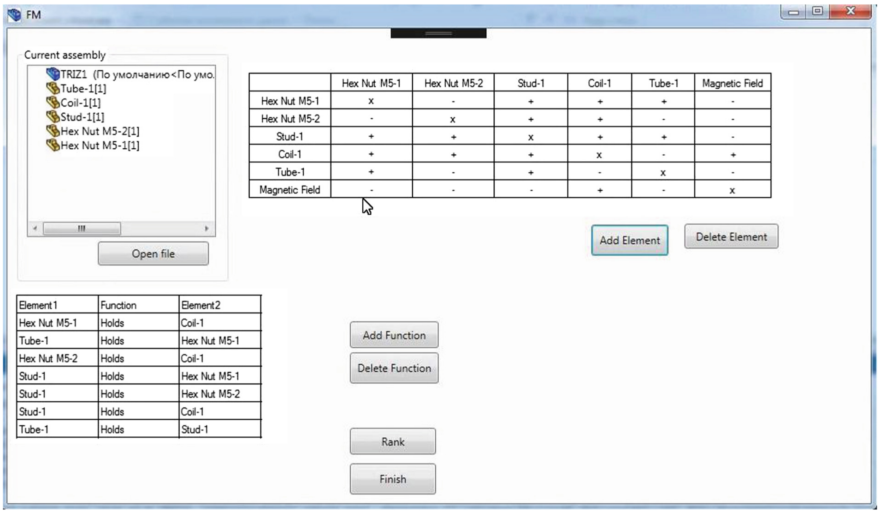


Fig. 1. Electromagnetic flow meter magnetic system.



	Hex Nut M5-1	Hex Nut M5-2	Stud-1	Coil-1	Tube-1	Magnetic Field
Hex Nut M5-1	x	-	+	+	+	-
Hex Nut M5-2	-	x	+	+	-	-
Stud-1	+	+	x	+	+	-
Coil-1	+	+	+	x	-	+
Tube-1	+	-	+	-	x	-
Magnetic Field	-	-	-	+	-	x

Element1	Function	Element2
Hex Nut M5-1	Holds	Coil-1
Tube-1	Holds	Hex Nut M5-1
Hex Nut M5-2	Holds	Coil-1
Stud-1	Holds	Hex Nut M5-1
Stud-1	Holds	Hex Nut M5-2
Stud-1	Holds	Coil-1
Tube-1	Holds	Stud-1

Fig. 2. Software for interaction analysis.

3.2 Case Study Function Analysis

The interaction matrix is created (Table 1) by using information received above; meanwhile, the interaction between elements is based in the mates of the CAD model. Also, the model elements are amplified with the element “magnetic field” (the element of the super system).

For interaction analysis algorithm presented in Sect. 2.2 is used. The mates “contact” and “concentric” are defined is an interaction of the elements in the function model.

Table 1. Interaction matrix for magnetic system

	Nut1	Nut2	Stud	Coil	Tube	Magnetic field
Nut1		−	+	+	+	−
Nut2	−		+	+	−	−
Stud	+	+		+	+	−
Coil	+	+	+		−	+
Tube	+	−	+	−		−
Magnetic field	−	−	−	+	−	

The second step is the functions identifying and function model creation. This step is based on the formal rules of the function identifying and the ranking. Results of this step are presented in the Table 2.

The step algorithm is the following: the initial rank is defined by means of the function model (Fig. 3); thereafter the ranking factor is solved by using the formula (1). For example, the ranking factor for the function “Nut1 holds Coil” is equal to 1. In this case, the function has the initial rank is equal to 1 and the element Nut1 has 3 links (with the tube, the stud and the coil). Additionally, the function is duplicated with two ones. Finally, the ranking factor of the function "Nut1 holds Coil" is equal to the ranking factor of the function "Stud holds Coil", but the distance between elements Stud and Coil is smaller than the second function. The distance between elements is defined as the distance between the centers of the mass in this case.

Meanwhile, the least ranking factor defines the most important function in the system – the Coil generates the Magnetic field. This function receives the higher rank of the system – 1. The remaining function receives the function rank with the increasing of the ranking factor.

In this case, the system is static, this means ranking factor and rank are time-independent. For the dynamic system calculation of the function, ranking factor is similar, but time factor takes into account.

Table 2. The function ranking

Element 1	Function	Element 2	Initial rank	Ranking factor	Final rank
Nut1	Holds	Coil	1	1 – 3 + 3 = 1	4B
Tube	Holds	Nut1	3	3 – 2 + 2 = 3	6
Nut2	Holds	Coil	1	1 – 2 + 3 = 2	5
Stud	Holds	Nut1	2	2 – 4 + 0 = −2	2
Stud	Holds	Nut2	2	2 – 4 + 0 = −2	2
Stud	Holds	Coil	1	2 – 4 + 3 = 1	4A
Tube	Holds	Stud	2	2 – 2 + 0 = 0	3
Coil	Generates	Magnetic field	0	0 – 4 + 0 = −4	1

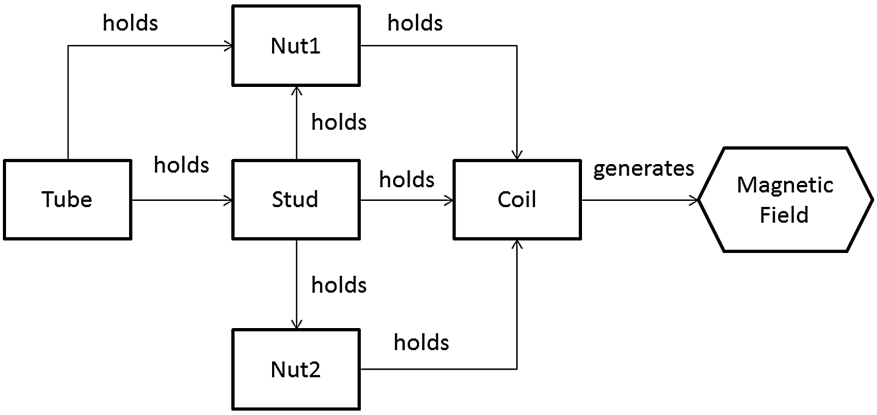


Fig. 3. Magnetic system function model

3.3 Case Study Trimming

The trimming is completed by using Fig. 3 and Table 2. In this case, the algorithm uses three formal trimming rules (Sect. 2.3). It starts with the lowest rank (function – “tube holds nut1”) and finishes with the higher rank function (the coil generates a magnetic field). As a result, three functions are highlighted to the trimming. Trimmed functions, these ranks, and trimming rules are presented in the Table 3.

Table 3. Trimmed functions and rules

Function	Rank	Trimming rules
Tube holds Nut1	6	Rule A. Function maybe trim if eliminate object of the function – Nut1
Nut2 holds coils	5	Rule C. Another component of the engineering system performs the useful function of the function carrier – e.g. stud
Nut2 holds coils	4B	Rule C. Another component of the engineering system performs the useful function of the function carrier – e.g. stud

The improved system is presented in the Fig. 4, and the function model is presented in the Fig. 5. The new system consists of the modified stud, the coil, and the tube. The stud holds the coil. The retention diameter of the stud is bigger than the diameter of the hole in the coil. Elements Nut1 and Nut2 are eliminated.

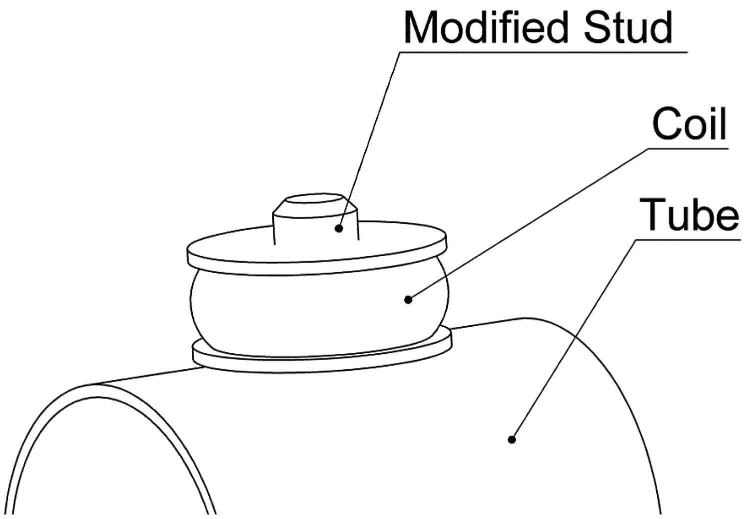


Fig. 4. Electromagnetic flow meter improved the magnetic system.

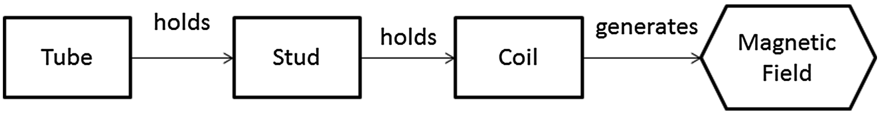


Fig. 5. Function model of improved magnetic system

The presented design of the electromagnetic flow meter is cheaper in mass manufacturing, and very easy to assemble. It means that the cost of an each flow meter in mass-production is lower. Also, this design of this device has small differences with the initial flow meter design. That means the cost of the transition to the new design is tiny.

The improved function model is less complicated and has a smaller number of elements. It means that the presented system is simpler. Ideality of this one is bigger than in initial system.

This example demonstrates that an implementation of the TRIZ-based software can provide the guidelines for the design development and improve, significantly reduce the number of iterations, reduce the design time and the number of errors and unsuccessful design at the in the conceptual design, detail design stages and for the patent around design.

4 Conclusions

In this paper, the method of the system development and improvement is presented with the example of the electromagnetic flow meter. The major steps and the procedures are explained in details.

The presented approach permits to improve and develop the system by means of the CAD model created in SolidWorks. This one permits to receive new design patterns and possibilities of the improvement and the development in the conceptual design, detail design stages and for the patent around design. The suggested method is an effort to transform the informal and uncertain design inventive process into the formal algorithm. The proposed algorithm is easy to use, simple, formal and may be used for all types of the CAD software with API (e.g. Inventor, SolidEdge, Kompas etc.).

The suggested method is an attempt to add the new possibilities in the work of the practical designers and developers. The simplicity of use makes it an ideal candidate for the integration with the different areas of industry and science.

5 Further Development

The further development goes in three areas – the verifying of presented approach, the automating of the trimming step and the design assessment.

For development and the verifying of the function ranking formal mechanism, patent analysis and collaboration with practice engineers will be used. In this instance, different types of system will be used (mechanics, electrics, pneumatics, complex systems etc.).

The development will be focused in the automatic trimming and semi-automatic one in the automatization area. In this case, the automation of the trimming process for dynamic and static systems of the different types (mechanical and not mechanical) will be developed.

For the development of the design assessment algorithm, the method of the collaboration with different techniques, such as Analytic hierarchy process (AHP) [24], Comparison (Pugh's) matrix [2] or other precise and fuzzy techniques [25] will be developed.

Acknowledgments. Authors would like to acknowledge EU Erasmus plus program and its project Open Innovation Platform for University-Enterprise Collaboration: new product, business and human capital development (Acronym: OIPEC, Grant Agreement No.: 2015-3083/001-001) for the support.

References

1. Ullman, D.: The Mechanical Design Process, 4th edn. McGraw-Hill, New York City (2010)
2. Pugh, S.: Creating Innovative Products: Using Total Design: The Living Legacy of Stuart Pugh. Addison-Wesley Publishers, Boston (1996)
3. Altshuller, G., Shapiro, R.: Psychology of inventive creativity. Issues Psychol. **6**, 37–49 (1956)
4. Di Gironimo, G., Carfora, D., Esposito, G., et al.: Improving concept design of divertor support system for FAST tokamak using TRIZ theory and AHP approach. Fusion Eng. Des. **88**, 3014–3020 (2013). doi:10.1016/j.fusengdes.2013.07.005
5. Chechurin, L.: TRIZ in science. Reviewing indexed publications. Proc. CIRP **39**, 156–165 (2016). doi:10.1016/j.procir.2016.01.182
6. Jupp, M.L., Campean, I.F., Travcenko, J.: Application of TRIZ to develop an in-service diagnostic system for a synchronous belt transmission for automotive application. Proc. CIRP **11**, 114–119 (2013). doi:10.1016/j.procir.2013.07.051
7. Yang, C.J., Chen, J.L.: Forecasting the design of eco-products by integrating TRIZ evolution patterns with CBR and simple LCA methods. Expert Syst. Appl. **39**, 2884–2892 (2012). doi:10.1016/j.eswa.2011.08.150
8. Akiyama, K.: Function Analysis: Systematic Improvement of Quality and Performance. Productivity Press Inc., Cambridge (1991)
9. Cooke, J.: TRIZ-based modelling and value analysis of products as processes. In: Trizfuture 2015, pp. 1–11 (2015)
10. Systems Engineering Fundamentals. https://ocw.mit.edu/courses/aeronautics-and-astronautics/16-885j-aircraft-systems-engineering-fall-2005/readings
11. API Support. https://www.solidworks.com/sw/support/api-support.htm
12. Ullah, A.M.M.S., Sato, M., Watanabe, M., Rashid, M.M.: Integrating CAD, TRIZ, and customer needs. Int. J. Autom. Technol. **10**, 132–143 (2016). doi:10.20965/ijat.2016.p0132
13. Chechurin, L.S., Wits, W.W., Bakker, H.M., Vaneker, T.H.J.: Introducing trimming and function ranking to SolidWorks based on functional analysis. In: Proceedings of the TRIZ Future Conference 2011, pp. 215–225 (2011)
14. Bakker, H.M., Chechurin, L.S., Wits, W.W.: Integrating TRIZ function modeling in CAD software. In: Proceedings of the TRIZfest-2011, p. 18 (2011)

15. Generative Design Software. Autodesk Within. http://www.autodesk.com/products/within/overview
16. Goldfire: Advanced Research, Problem Solving & Analytics. https://www.ihs.com/products/design-standards-software-goldfire.html
17. Ilevbare, I.M., Probert, D., Phaal, R.: A review of TRIZ, and its benefits and challenges in practice. Technovation **33**, 30–37 (2013). doi:10.1016/j.technovation.2012.11.003
18. Li, M., Ming, X., He, L., et al.: A TRIZ-based trimming method for patent design around. CAD Comput. Aided Des. **62**, 20–30 (2015). doi:10.1016/j.cad.2014.10.005
19. Ikovenko, S., Litvin, S., Lyubomirskiy, A.: Basic Training Course. GEN3 Partners, Boston (2005)
20. Efimov-Soini, N.K., Chechurin, L.S.: Method of ranking in the function model. Proc. CIRP **39**, 22–26 (2016). doi:10.1016/j.procir.2016.01.160
21. Efimov-Soini, N., Chechurin, L., Renev, I., Elfvengren, K.: Method of time-dependent TRIZ function ranking. In: TRIZ Future Conference 2016: Systematic Innovation and Creativity (2016)
22. Efimov-Soini, N., Uzhegov, N.: The TRIZ-based tool for the electrical machine development. In: Progress in Electromagnetic Research Symposium (2017)
23. Gadd, K.: TRIZ for Engineers: Enabling Inventive Problem Solving, 1st edn. Wiley, Hoboken (2011)
24. Saaty, T.: The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill, New York City (1980)
25. Efimov-Soini, N., Kozlova, M., Collan, M., Passi, L.: A multi-criteria decision-making tool with information redundancy treatment for design evaluation. In: Proceedings of NSAIS 2016 Workshop on Adaptive and Intelligent Systems, pp. 73–75 (2016)

Publication IV

Efimov-Soini, N. and Elfvengren K.
Method of system model improving using TRIZ function analysis and trimming.

Reprinted with permission from
Advances in systematic creativity.
pp. 115-131

A method of system model improvement using TRIZ function analysis and trimming

Nikolai Efimov-Soini and Kalle Elfvengren

Lappeenranta University of Technology, School of Business and Management

Abstract This chapter presents a method of system model improvement by means of system complexity reduction, based on TRIZ function analysis and trimming. The suggested method can be used for new development as well as improvement of an existing system. The presented approach is illustrated by an industrial case study.

Keywords: TRIZ, function analysis, trimming.

1 Introduction

The chapter concerns a function-based method for design improvement and new design development. According to Ullman, 75% of product cost is defined at the conceptual stage, and the cost of product improvement grows exponentially in the manufacturing stage, but the use of systematic methods makes it possible to minimize the funds lost (Ullman 2010). This means that these stages are extremely important in the product life-cycle, and the use of systematic methods at these stages is thus very useful for design development.

Several systematic approaches exist, e.g. Axiomatic Design (Suh 1990), USIT (Sickafus 1997), and TRIZ (Altshuller 1984). In this chapter, the TRIZ methodology is used for design development, because it is easy to use and understand. TRIZ utilizes formal approaches and inventive tools, and it is widely used in science and industry (Luo et al. 2012; Di Gironimo et al. 2013; Chechurin 2016).

TRIZ, in Russian *Theoria Resheniya Izobretatelskih Zadech*, or Theory of Inventive Problem Solving, is an inventive method proposed by the Soviet inventor Genrich Altshuller in 1956 (Altshuller and Shapiro 1956). He studied about 40 000 patents and drew out the formal processes for some new ideas of the generation and the technical evolution trends. The method has 40 inventive principles, contradictions, ideality, and patterns of evolution.

This chapter concerns modern TRIZ tools, such as function analysis and trimming (Gadd 2011). The latter is a formal method for system development and improvement, based in the reduction of system complexity. Different types of this tool are used for patent-around design (Li et al. 2015), system improvement (Sheu and Hou 2013), and to form new design patterns (Efimov-Soini and Uzhegov 2017). In this chapter, the advanced method of trimming is used for system improvement and development in a formal manner. Function analysis is used as the input to the trimming process.

Previous trimming methods used formal rules for step-by-step improvement of the system (Ikovenko et al. 2005; Sheu and Hou 2013; Li et al. 2015). The functions were independent in these approaches, and the authors did not use a special formal ranking index to define the importance of the function in the system. In contrast to the previous methods, the new approach takes the relation between the functions and elements into account. The function analysis step is improved and a new operation “creation and analysis of the function interaction matrix” is added before the trimming step. This improvement highlights the “function streamlines” in the system. This means that the functions are grouped in sets. This idea makes it possible to automate the trimming algorithm and to receive a new concept pattern.

The rest of the chapter is structured as follows: section 2 is devoted to the state-of-the-art, section 3 describes the method, in section 4 the method is illustrated by an industrial case study, section 5 consists of discussion, and conclusions are presented in section 6.

2 State-of-the-art

The functional part of the presented method is based on TRIZ function analysis. There are several types of function presentation of the system model, such as the Functional Flow Block Diagram (FFBD) (Akiyama 1991), the Functional Analysis System Technique (FAST) (Cooke 2015), the Integrated Computer-Aided Manufacturing Definition for Function Modeling (IDEF0) (Defense Acquisition University 2005). All these methods use the function approach for system model presentation. For example, FFBD is a function-oriented approach based on the sequential relationship of all system functions. FFBD develops the system from the top to the bottom and proposes a hierarchal view of the functions across a series of levels. The aim of each level is to identify a single task on a higher level by means of functional decomposition. In comparison to FFBD, FAST diagram focuses on the product functions rather than a specific design. In contrast to FFBD and FAST, the TRIZ function modeling takes account of the physical interaction between the system elements and the type of this interaction. There are four interaction types: useful, harmful, insufficient, or excessive. FFBD and FAST use the static approach in the function analysis, meaning that the number of elements and functions, and the relation between the elements are time-independent and do not change in time, whereas many TRIZ practitioners point out the need to identify problems clearly at each system level, and to solve them separately. This goal is achieved by integrating well-known models and instruments for system description and function representation. O. and N. Feygenson also suggest the Advanced Function Approach in the Modern TRIZ (Feygenson and Feygenson 2016), where they add some steps, such as: “Indicate the place the function is performed” and “Indicate the time the function is performed”. Also this approach has been used by Litvin et al. (2011) in their research in the application history and the function analysis evolution. The research indicates that the next logical step for enhancing the Function Approach is the introduction of two parameters: “time of performing a function” and “place of performing a function”. The presented method combines previous works in the domain and proposes taking the physical relation and time-dependence of the system model into account.

The second part of the method consists of trimming. This is a formal process to improve the system model by means of system complexity reduction. There are different approaches in this case. For example, Miao Li’s method (Li et al. 2015) is used in the patent around design. It takes account of the importance of each element. The Gen3 method (Ikovenko et al. 2005) is used for design improvement and development. This method uses the formal functional approach to rank the importance of each function in the system. The approach presented in this chapter combines and supplements these methods, and collects previous works in this domain.

3 Method description

This chapter contains the method description by using a simple example. The method uses function modeling for system model improvement by means of system complexity reduction. The suggested method consists of two main parts: function analysis and trimming.

3.1 Function presentation and other definitions

In TRIZ function modeling, the functions are presented in the following manner: the tool (the function carrier), the function, and the object. The function must create real action from the tool to the object, e.g. “a helmet deflects a bullet” is a legitimate function, but “a helmet protects a head” is not a legitimate function. On the other hand, the function does not be declarative, e.g. “a pill improves the health”.

The function rank is a formal factor which defines the importance of the function in the function model. In this case, the rank is a positive integer number. As such, the argument of the rank function is inversely proportional to the importance of the function. For example, a function with rank three is more important than a function with rank five.

The ranking factor is a formal index which defines the function rank. It is a rational number and maybe positive or negative. The latter is also inversely proportional to the importance of the function. Thus, a small value defines the most important function.

The target element is called the main element in the system. This means that this element defines the purpose of the system in the initial function model.

The target function is a function which interacts with the target element. On the other hand, this function defines the main function of the initial system.

3.2 Function analysis

The function analysis part consists of three main steps: component analysis, interaction analysis and function modeling. Component analysis concerns decomposition of the system model to the main parts, e.g. to big assemblies. This step may be done by means of CAD model analysis (Efimov-Soini and Chechurin 2017). In the interaction analysis step, the interaction between the elements is defined. In the final step, a function diagram (function model) is created and the rank (importance) of the functions in the system is defined.

3.2.1 Component analysis

This step concerns system model decomposition. Complex systems are usually divided into big assemblies and simple systems to parts. This analysis includes not only system model parts, but also external parts. For example, a car consists of an engine, a frame, a body etc., but in some cases a road may be included in the system model. The main goal of this step is to create a detailed system decomposition model in the area close to the target element.

3.2.2 Interaction analysis

A special interaction matrix is used in the interaction analysis step. In this matrix, the interaction between the elements of the system model is denoted with a plus sign (+) and the lack of interaction with a minus sign (-). As an example, the interaction matrix of the system a cup with a cap – coffee, is presented in Table 8.1. This system model is used below to illustrate the method description. The case study is illustrated with a real industrial case.

Table 8.1 – An interaction matrix

	cup	**table**	**coffee**	**cap**
cup	■	+	+	+
table	+	■	**-**	**-**
coffee	+	**-**	■	+
cap	+	**-**	+	■

3.2.3 Function modeling

There are six substeps in this step: definition of the interaction as a function, initial ranking, initial function model creation, model selecting, final ranking, and function interaction analysis.

Firstly, each interaction is defined as a function in the substep called “interaction definition as a function”. If interaction between the elements is not available, the function is not defined. The functions in the system model are presented in Table 8.2.

Table 8.2 – Functions in the system model

Element 1	**Function**	**Element 2**	
cup	holds	coffee	target function
table	holds	cup	
cap	holds	coffee	
cup	holds	cap	

The target function and the target element are also defined in this step. In this case, the target function is “cup holds coffee” and the target element is “coffee”.

Next, the initial function rank is defined. The rank (importance) of each function is defined on the interval (1…+∞). When the initial rank of the target function is 0, it is the highest in the system. The initial ranking of the suggested system is presented in Table 8.3.

Table 8.3 – Initial ranking

Element 1	**Function**	**Element 2**	**Rank**
cup	holds	coffee	0
table	holds	cup	1
cap	holds	coffee	1
cup	holds	cap	1

After this, the function model is created by means of the previous step results. At this point, it is possible to create the function model simultaneously with the initial rank definition. In the function diagram, the elements are marked as rectangles. It is also recommended to place the target element in the right side. In addition, for elements which are impossible to modify or are not included in the model, create action (e.g. gravitation) is noted with a hexagon. The function model of the suggested case is presented in Figure 8.1.

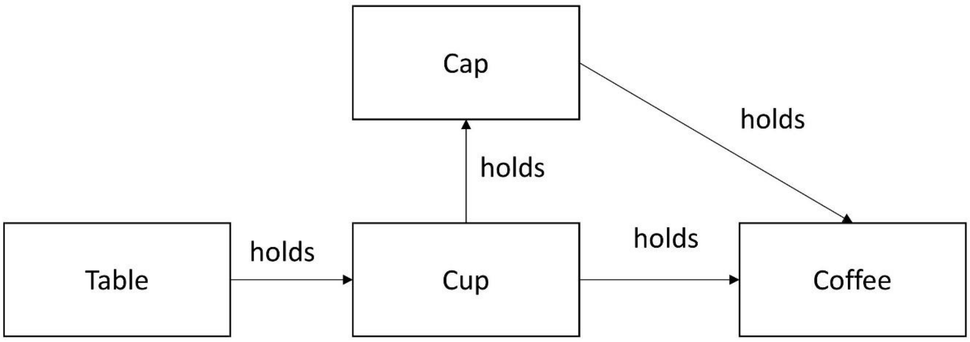


Figure 8.1 – The function model

In the suggested method, two model types are presented: static and dynamic. In the static model the function rank (importance), the interaction number in the system, and the number of the elements in the system are permanent. On the other hand, one or all parameters can be changed in a dynamic model. The dynamic model is presented as a set of system snapshots. Each snapshot is a static state of the system, which means that the function rank, the number of interactions and the number of elements are permanent in each state. For each static state, the time (duration) of each snapshot is defined by means of the following formula:

$$t_{ni} = \frac{t_i}{t_w} \qquad (1)$$

where t_{ni} is the normalized time of the state i, t_i – the time of the state (in minutes, seconds, years etc.) and t_w is the total observation time (in minutes, seconds, years etc.).

The presented approach is used to calculate the final function rank. In this case, the special formal index (the ranking factor) is used. The latter is inversely proportional to the importance of the function. Thus, a small value of ranking factor defines the most important function. Using normalized time, the final ranking factor is defined as

$$FFR = \sum FR_i \times t_{ni} \quad (2)$$

where FFR is the final ranking factor, FR_i is the ranking factor in state i, and t_{ni} is the normalized time of the state i. For a static system, t_{ni}=1.

For the presented system, both the dynamic and the static approach may be used. For the dynamic approach, two states are considered, the cup is on the table (tn_1=0.9) and the cup is lying on its side (tn_2=0.1).

In the final ranking substep, the special index, called the ranking factor, is added to define the function rank. The following formula is used to calculate this:

$$FR_i = R - N_l - N_d \quad (3)$$

where FR_i is the ranking factor in this state, R is the initial rank, N_l is the number of function carrier links, N_d is the number of duplicated functions. The final ranking is presented in Table 8.4.

Table 8.4 – Final ranking

Element1	Function	Element2	R	Nl	Nd	FR	Final rank
cup	holds	coffee	0	3	0	-3	1
table	holds	cup	1	1	0	0	3
cap	holds	coffee	1	2	0	-1	2B
cup	holds	cap	2	3	0	-1	2A

Additional subindexes are used in the suggested case, such as 2A and 2B. The letter is used to distinguish functions with an equal ranking factor. The function with subindex A is geometrically closer than the function with subindex B. This means that the element “cup” is closer to the element “coffee” than the element “cap” to the element “coffee”.

The situation is different in the dynamic model, and the situation is different in the dynamic approach as well. There are two system states: the cup is on the table (tn_1=0.9) and the cup is lying on its side (tn_2=0.1). The latter state function model is equal to the model in the static approach. For the other case, the function model is presented in Figure 8.2.

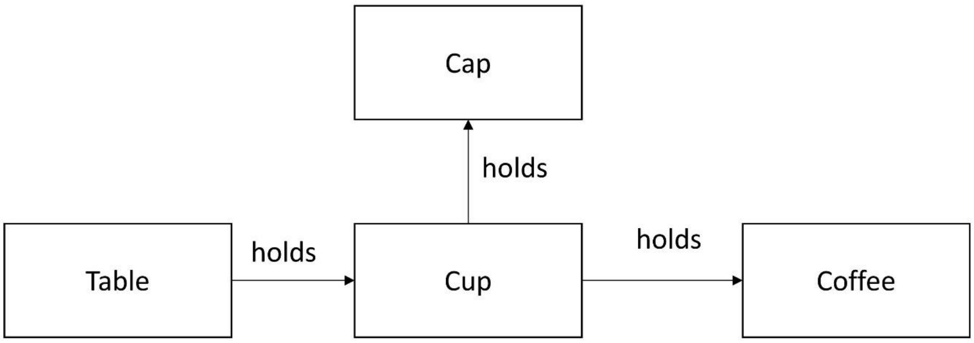


Figure 8.2 – The function model for the state tn_2.

The function “cap holds cup” is not available in this state, because these elements do not interact here. The ranking table for this case is presented below.

Table 8.5 – Ranking in the dynamic approach

Element1	**Function**	**Element2**	**R1**	**R2**	**Nl1**	**Nl2**	**Nd**	**FR1**	**FR2**	**Final rank**
cup	holds	coffee	0	0	3	3	0	-3*0.9	-3*0.1	1
table	holds	cup	1	1	1	1	0	0*0.9	0*0.1	4
cap	holds	coffee	1	NA	2	2	0	-1*0.9	-1*0.1	3
cup	holds	cap	2	2	3	3	0	-1*0.9	-1*0.1	2

Finally, sets of functions are defined after ranking. This approach makes it possible to improve the trimming process and to receive some new design patterns. In this case, the functions are divided into three types: independent (-), dependent (+) and equal (=).

Independent functions do not interact – e.g. in the fun system, functions installed in the wall "wall holds fun" and "fun moves air" are independent. In the dependent type, functions create the result "together", e.g. "bolt holds nut" and "nut holds plate" are dependent functions. The equal functions create a similar result in the system, e.g. functions "welding holds plate" and "bolt holds plate" are equal in many cases. In this case, independent functions trim in a separate manner, and dependent and similar functions in sets. The function interaction matrix for the presented model is shown in Table 8.6.

Table 8.6 – The function interaction matrix

	cup holds coffee	table holds cup	cap holds coffee	cup holds cap
cup holds coffee	■	-	=	-
table holds cup	-	■	-	-
cap holds coffee	=	-	■	+
cup holds cap	-	-	+	■

There are two sets of functions, the dependent set "cup holds cap" and "cap holds coffee" and the set of equal functions "cup holds coffee" and "cap holds coffee".

3.3 Trimming

Trimming is a formal process to improve the system model by means of system complexity reduction. There are three formal rules. The function may be trimmed if

a) An object of the Function does not exist

b) An object of the Function performs the function itself

c) Another Engineering System Component performs the useful function of the Function Carrier.

The trimming procedure starts with the function with a lower rank. If sets of function are defined in the system model, the trimming process starts with the last one. Three formal rules are used to trim the sets in the trimming process. This is a radical method, but it makes it possible to gain a new qualitative design pattern.

In the presented case the trimming process has the following steps:

- ‘Cup holds cap’ and ‘cap holds coffee’ (set ”cup holds coffee”) may be trimmed in case of the transfer function. For example, the function “holds” is transferred to the table and the new system is a table with a thermos. Another example: the function transfers to coffee itself to create a solid shell of coffee. In this case, the coffee holds itself. This trimming process is similar to the previous one.
- ‘Table holds cup’. This function has a lower rank in the system (in the static and dynamic approaches) and maybe trimmed by means of rule B. It is possible to place the cap on the floor or hold it in the hand.
- ‘Cap holds coffee’ may be trimmed if the function is transferred to the cap (similar to a baby cup). In this case, the element “cap” is trimmed, and as well the function “Cup holds cap” is trimmed as well by means of rule A.

4 Case study

The industrial case is presented in this chapter. The case concerns a special tool for flow meter assembling. This procedure is used by the firm *Termotronic* (Saint-Petersburg, Russia) in the manufacturing process. The presented mechanism is very complex, and therefore this chapter focuses only on the flow meter holding system. The step-by-step algorithm is presented below.

The holding system is presented in Figure 8.3. The system is inspired with a linear actuator and it is used to hold the flow meter on a vertical axis. Considering that the various flow meter models have different tube diameters, the system must be adaptive. In this case, a system based in pinions is used. The user rotates a handle, this handle rotates the first pinion, then the pinion rotates the driven pinion, and the last one moves the thread. In this process, the thread moves the holder on the horizontal axis. The frame in this system holds the holder.

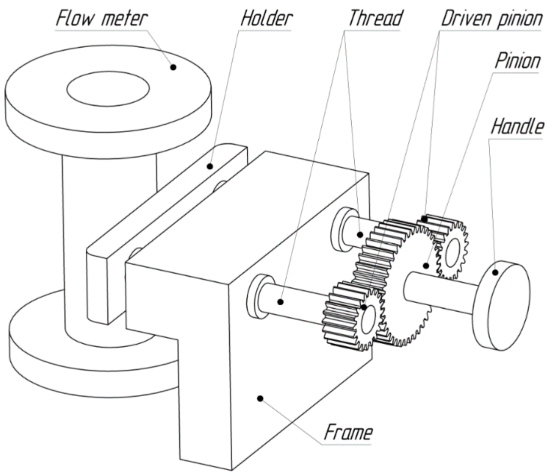


Figure 8.3 – Initial flow meter holding system

4.1 Function analysis of the holding system

The first step in the suggested approach is function analysis. This approach is based on previous developments (Efimov-Soini and Chechurin 2016; Efimov-Soini et al. 2016; Efimov-Soini and Uzhegov 2017) and the Gen3 function analysis approach (Ikovenko et al. 2005).

There are three parts on this step: component analysis, interaction analysis and function analysis. The first and second steps are accomplished by means of a special software (Efimov-Soini and Chechurin 2017) which uses a CAD model of the flow meter holding system.
The function model of the holding system is presented in Figure 8.4.

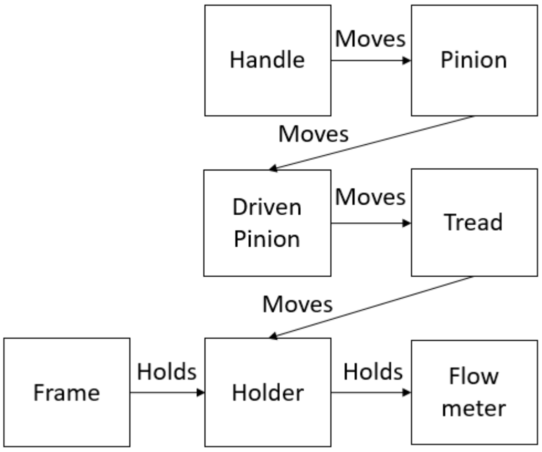


Figure 8.4 – Function model of the holding system

4.2 System function interaction matrix

The interaction between the functions and the interaction type are defined in this step. There are three types of the interaction in the suggested method: dependence (+), independence (-) and similarity (=). In Table 8.7, independent and dependent functions are distinguished. By means of this table, it is possible to divide the functions into two parts, the function “Frame holds Holder” and a set of the five remaining functions, named t “Handle moves Holder”.

Table 8.7 – Holding system function interaction table

	Handle moves Pinion	Pinion moves driven pinion	Driven pinion moves Tread	Tread moves Holder	Holder holds Flow meter	Frame holds Holder
Handle moves Pinion	■	+	+	+	+	-
Pinion moves Driven pinion	+	■	+	+	+	-
Driven pinion moves Tread	+	+	■	+	+	-
Tread moves Holder	-	+	-	■	+	-
Holder holds Flow meter	+	+	+	+	■	-

Frame holds Holder	-	-	-	-	-	

4.3 Trimming of the system

The system simplification is completed by means of a trimming algorithm in this step. There the set of functions "Handle moves Holder" and the function carriers of this set are transformed to the system "Handle-Spring-Holder". This means that a spring is added into the system and the functions set "Handle moves Holder" is trimmed by means of Rule C. This system is self-adaptive, which means that the spring holds the flow meter with a different pipe diameter without any action. The function model of the improved system is presented in Figure 8.5. The improved system is presented in Figure 8.6.

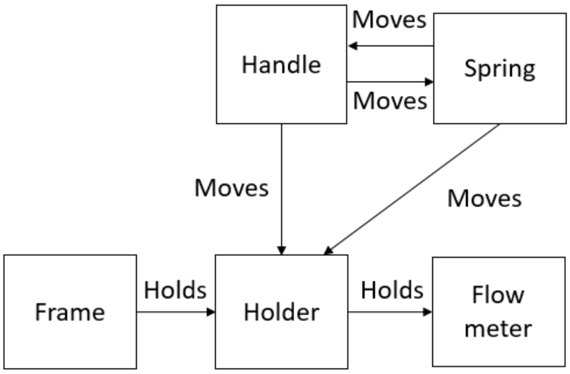


Figure 8.5 – Function model of the improved holding system

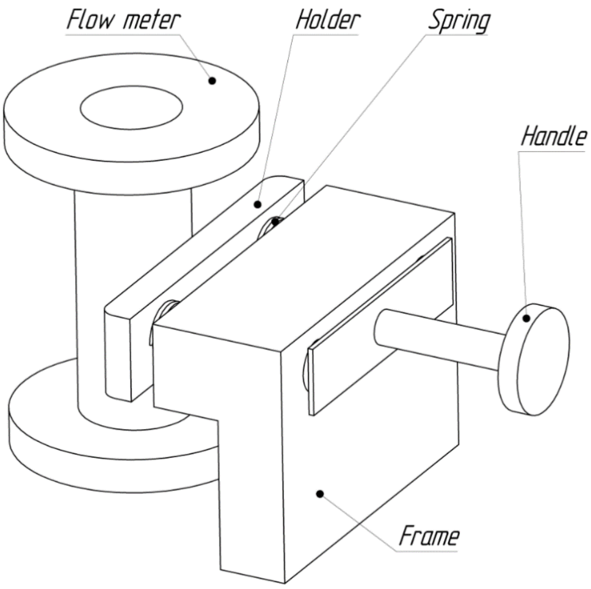


Figure 8.6 – Improved holding system

5 Discussion

A special survey was performed to verify the presented algorithm. In this survey, 10 engineers from the firm *Termotronic* and *Institut Telecomunicatsiy* improved the existing systems by using the suggested method. They worked manually without any special tool for system decomposition and function ranking to understand the weakness of this approach better. All specialists commended the new design pattern received by means of this method. 8 of the 10 engineers mentioned the difficulty of calculation in complex assemblies and 7 of the 10 mentioned the ambiguity of the functional definition.

6 Conclusions

The presented algorithm makes it possible to improve a system model by means of system function presentation. It takes account of the evolution of the situation (and therefore its function model) and shows how the approach yields trimming ideas that are different from what can be derived from the standard static function ranking procedure. In addition, it is believed that the introduction of the time domain makes function analysis more accurate and realistic. The function analysis is formularized and requires a number of calculations, but makes it possible to create the improvement in a systematic manner.

Acknowledgments

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

References

Akiyama, Kaneo. *Function Analysis: Systematic Improvement of Quality and Performance*. Cambridge MA: Productivity Press Inc., 1991.

Altshuller, Genrich. *Creativity as an Exact Science*. New York: Gordon and Breach, 1984.

Altshuller, Genrich, and Rafael Shapiro. "Psychology of Inventive Creativity." *Issues Psychological* 6 (1956): 37–49.

Chechurin, Leonid. "TRIZ in Science. Reviewing Indexed Publications." *Procedia CIRP* 39 (2016): 156–165. https://doi.org/10.1016/j.procir.2016.01.182.

Cooke, John. "TRIZ-based Modelling and Value Analysis of Products as Processes", *Trizfuture 2015*, (2015): 1–11.

Defense Acquisition University. *System Engineering Fundamentals*. Virginia USA: Defense Acquisition University Press, 2005. https://ocw.mit.edu/courses/aeronautics-and-astronautics/16-885j-aircraft-systems-engineering-fall-2005/readings/sefguide_01_01.pdf.

Efimov-Soini, Nikolai, Leonid Chechurin, Ivan Renev, and Kalle Elfvengren."Method of Time-dependent TRIZ Function Ranking", *Procedia CIRP: TRIZ Future 2016*.

Efimov-Soini, Nikolai and Leonid Chechurin. "The Method of CAD Software and TRIZ Collaboration." In *Creativity in Intelligent Technologies and Data Science*, edited by A. Kravets, M. Shcherbakov, M. Kultsova, P. Groumpos, Communications in Computer and Information Science, vol. 754, Springer, Cham (2017): 517–527.

Efimov-Soini, Nikolai and Leonid Chechurin. 2016. "Method of Ranking in the Function Model", *Procedia CIRP* 39, (2016): 22–26.

Efimov-Soini, Nikolai and Nikita Uzhegov. "The TRIZ-based Tool for the Electrical Machine Development." *Progress in Electromagnetics Research Symposium*, St Petersburg, Russia, 22–25 May 2017.

Feygenson, Oleg. and Naum Feygenson. "Advanced Function Approach in Modern TRIZ." In *Research and Practice on the Theory of Inventive Problem Solving (TRIZ)*. Cham: Springer International Publishing, (2016): 207–221.

Gadd, Karen. *TRIZ for Engineers: Enabling Inventive Problem Solving*. United Kingdom: Wiley, 2011.

Di Gironimo, Guiseppe, D. Carfora, G. Esposito, C. Labate, R. Mozillo, F. Renno, A. Lanzotti, and M. Suiko. "Improving Concept Design of Divertor Support System for FAST Tokamak Using TRIZ Theory and AHP Approach." *Fusion Engineering and Design* 88, no. 11 (2013): 3014–3020. https://doi.org/10.1016/j.fusengdes.2013.07.005.

Ikovenko, Sergei, Simon Litvin, and Alex Lyubomirskiy. *Basic Training Course*, Boston: GEN3 Partners, 2005.

Li, Miao, Xinguo Ming, Lina He, Maokuan Zheng, and Zhitao Xu. "A TRIZ-based Trimming Method for Patent Design Around." *CAD Computer Aided Design* 62 (May 2015): 20–30. https://doi.org/10.1016/j.cad.2014.10.005.

Litvin, Simon, Naum Feygenson, and Oleg Feygenson. "Advanced Function Approach." *Procedia Engineering* 9 (2011): 92–102. https://doi.org/10.1016/j.proeng.2011.03.103.

Luo, Yihong, Yunfei Shao, and Ting Chen. "Study of New Wall Materials Design Based on TRIZ Integrated Innovation Method." *Management Science and Engineering* 6, no. 4 (2012): 15–29. http://dx.doi.org/10.3968/j.mse.1913035X20120604.635.

Sheu, Daniel, and Chun Hou. "TRIZ-based Trimming for Process-machine Improvements: Slit-valve Innovative Redesign." *Computers & Industrial Engineering* 66, no. 3 (2013): 555–556. https://doi.org/10.1016/j.cie.2013.02.006.

Sickafus, Ed. *Unified Structured Inventive Thinking: How to Invent*. USA, MI: Ntelleck, 1997.

Suh, Nam. *The Principles of Design*. New York: Oxford University Press, 1990.

Ullman, David. *The Mechanical Design Process*. 4th ed. New York: McGraw-Hill, 2010.

Publication V

Uzhegov, N., Efimov-Soini, N. and Pyrhonen J.
Assessment of Materials for High-speed PMSMs Having a Tooth-coil Topology.
Reprinted from
Progress In Electromagnetics Research M
vol. 51, pp. 101-111., 2016
Open publication

Progress In Electromagnetics Research M, Vol. 51, 101–111, 2016

Assessment of Materials for High-Speed PMSMs Having a Tooth-Coil Topology

Nikita Uzhegov[1, *], Nikolai Efimov-Soini[2], and Juha Pyrhönen[1]

Abstract—In this paper, materials frequently used in high-speed (HS) electrical machines are assessed. High-speed permanent magnet synchronous machines with a special tooth-coil topology serve as an example for the assessment. The lamination and rotor sleeve materials are compared taking into account their price, per unit losses, resistivity, and other factors. The resulting tables provide the electrical machine designer with a means to enhance the HS machine performance at low costs.

1. INTRODUCTION

According to the increasing number of publications on the topic [1–3], the interest of the research community in high-speed (HS) electrical machines is growing. The multidisciplinary nature of the HS electrical machine design procedure attracts researchers from the fields of electromagnetics, thermal analysis, rotordynamics, power electronics, material science as well as bearing designers [4–8]. Intensive studies in the field are motivated by the industry's interest in these machines. Application fields of HS machines cover water treatment, energy sector, heating, ventilation, and air conditioning (HVAC), and food industry. The advantages of HS motors and generators have made these machines attractive in various application fields. These advantages are a higher system efficiency, a smaller carbon footprint and system size, and a higher power density compared with conventional rotating electrical machines [9].

High-speed induction machines (HSIM) and permanent magnet synchronous machines (PMSM) are the most attractive and widespread solutions in the industry. The HS PMSM provides a higher efficiency and power density and a higher power factor than the HSIM, especially in low-power applications [10, 11].

In this paper, a special HS PMSM topology is considered. The machines under study have six stator slots and nonoverlapping concentrated windings, that is, tooth-coil (TC) windings. The rotor has two poles and consists of a full cylindrical permanent magnet (PM) and a retaining sleeve around the PM. The advantages of this topology are the simple rotor and stator construction and assembly process, a high efficiency and power factor, a sinusoidal back-EMF shape, and a short axial protrusion length of the end windings. The short end windings allow to achieve a short rotor length, which, in turn, increases the maximum rotational speed [12, 13].

A low number of poles is preferable in high-speed machinery because of the converter limitations and a significant increase in some loss components at high nominal frequencies [14]. In the case of a 2-pole HS PMSM with distributed windings (DW), the axial protrusion length of the end windings can be equal to the stator active length. Therefore, the rotor is longer, which further complicates the design of the drive train. This problem can be avoided by using tooth-coil windings. However, there are several factors that limit the adoption of the proposed topology with TC windings.

This paper describes some design solutions aimed to increase the power or rotational speed of the HS PMSM having the above-mentioned topology. The effects of the selection of the stator and rotor

---

Received 6 August 2016, Accepted 18 October 2016, Scheduled 28 October 2016

[*] Corresponding author: Nikita Uzhegov (nikita.uzhegov@lut.fi).

[1] Department of Electrical Engineering, School of Energy Systems, Lappeenranta University of Technology (LUT), Lappeenranta 53851, Finland. [2] Department of Operation Management and Systems Engineering, School of Business and Management, LUT, Lappeenranta 53851, Finland.

materials on the machine performance and costs are presented. The design solutions are elaborated on and compared with each other by two analyses.

There are various methods to assess an engineering system design; however, only a few of them are widely used in the industry [15]. This paper focuses on two popular methods, namely, the Pugh matrix and the Analytical Hierarchical Process (AHP).

The main contribution of this paper is the description of materials enabling a higher power or rotational speed of HS machines and a comparison of these materials with each other. This information will facilitate material selection based on the performance/complexity ratio. The data are validated by prototypes constructed and measured in the study. The proposed methods of comparison can be applied to other design optimization options and other electrical machine types.

2. CONSTRUCTION AND KEY LIMITATIONS

The design of any high-speed electrical machine is a multidisciplinary process owing to the mechanical, thermal, and electromagnetic aspects to be taken into account simultaneously. In the case of HS electrical machines, the electromagnetic design is more complicated than with conventional machines. After the electromagnetic design is completed, a detailed thermal and rotordynamic analysis must be performed. If any of the boundaries is not met, a new round of iteration starts.

This paper proposes a material selection strategy that can help to overcome the boundaries set by the thermal, mechanical, and electromagnetic limitations. An HS electrical machine topology serves as an example to demonstrate the influence of every design solution in detail. Two prototypes based on the proposed topology were constructed and measured. In these machines, alternative design approaches were adopted to overcome the limitations. These methods of comparison can also be applied to any other electrical machines.

The topology under consideration is aimed to reduce the manufacturing costs. To this end, there are only six stator slots in the topology. The rotor consists of a full cylindrical diametrically magnetized PM inside a retaining sleeve. Fig. 1 illustrates the cross-section of the HS topology with an example of the flux lines, flux distribution, and winding scheme. The Finite Element Method (FEM) calculations of the machines were performed using the Cedrat Flux software package. All calculations were made in 2D; however, the 3D effects were taken into account using the method described in [16]. A detailed description of the FEM design process of the tooth-coil machine topology can be found in [17].

The structural limitations of the topology are mainly related to the stresses between the retaining sleeve and the magnet. These stresses are caused by centrifugal forces and thermal expansion. The contact between the PM and the retaining sleeve must be maintained from zero up to the maximum allowed rotational speed and at any operating temperature. Simultaneously, the stresses between the

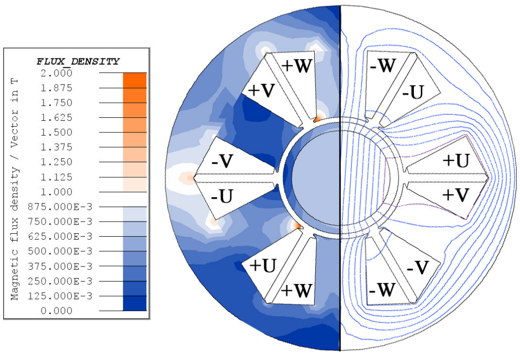


Figure 1. Cross-section of the tooth-coil topology under investigation. The rated point flux density and flux line distribution are shown in the example machine. The winding scheme is demonstrated.

PM and the sleeve must be below the yield strength of the retaining sleeve material taking into account the safety factor [18].

The maximum length of the machine is associated with the rotordynamics. Usually, the drive system is designed to be undercritical. However, there are bearing solutions that allow overcritical operation. In the topology under consideration, the rotordynamics is usually not a critical limitation. Because of the TC windings, the total rotor length is significantly shorter than with a DW machine of a similar performance. The shorter rotor enables undercritical operation in most of the cases with the topology under study.

The losses place significant limitations both on the rotor and stator parts. The rotor losses consist of magnet and retaining sleeve losses caused by eddy currents. Further, about three-quarters of the total rotor losses occur in the conducting retaining sleeve material. The total rotor losses do not significantly reduce the machine efficiency, but they can cause permanent magnet overheating and ultimately, irreversible demagnetization.

The stator core losses are a limiting factor at high operating frequencies. Reliable loss data at high frequencies are required to adjust the coefficients of the applied hysteresis loss model and calculate the core losses at the nominal frequency by the FEM.

In this topology, copper losses can be very high, because the winding factor is only 0.5. In the winding design, it is extremely important to limit extra copper losses, including losses caused by the skin effect and circulating currents. An analysis of the prototypes has shown that the rotor and end winding temperatures are the two main thermally critical factors. These temperatures can be selected as the key indicators of whether the current design meets the boundary conditions.

Mechanical losses start to play a significant role at high rotational speeds. Because of the smooth outer rotor surface and a relatively small rotor diameter, friction and windage losses are not a limiting factor. In the case of ball, air film, or fluid film bearings, bearing losses constitute the majority of the mechanical losses in the topology under analysis. The frequency converters may be a limiting factor at high frequencies even in two-pole machines. To minimize the losses in the machine, various converter topologies, sampling techniques, and switching frequencies are used [19, 20].

There are various alternatives to overcome the above-mentioned multidisciplinary limitations and achieve a better performance with the topology presented in this paper. These solutions require diverse resources at the design and manufacturing stages and yield different results. The following section introduces methods that allow to compare alternative solutions and rank them. By applying the results of this comparison, design engineers are able to select the most promising materials.

3. ASSESSMENT METHODS

Two methods are frequently applied to the design assessment: the Pugh matrix [21] and the Analytical Hierarchical Process (AHP) [22]. The AHP is used for concept ranking and the Pugh matrix for pairwise comparison.

In the Pugh matrix method, the concepts are compared with the "datum" concept with respect to several parameters. Thus, a value "better than datum," "worse than datum," or "similar" is determined for each parameter. The best design has the highest number of "better than datum" values. This method is widely used in various areas, for example, in energy and mechanical engineering, and it can also be integrated with other methods such as the Quality Function Deployment (QFD) [23–26].

The AHP is a method developed by Professor T. L. Saaty in 1977, and it is based on the decomposition of the main problem into subproblems. The method consists of two main phases: ranking of the evaluation criteria and assessment of the design. In order to achieve the goal, pairwise comparisons of all criteria are carried out to determine the relative importance of each criterion. Next, pairwise comparisons are made between all alternatives separately for each criterion. Based on these comparisons, an overall selection is made. Eigenvalues and eigenvectors are used to ensure that the decision maker's judgments are consistent [27]. This method is used for electrical machine design [28], measurement system development [29], and electrical energy generation planning [30, 31].

A fair comparison of diverse parameters can be made by using normalized data. For normalization, the following formulas are used:

$$f_{\text{norm}} = \begin{cases} \dfrac{f_{\text{initial}} - f_{\min}}{f_{\max} - f_{\min}} - \text{ if } f_{\max} \text{ is the best value,} \\ 1 - \dfrac{f_{\text{initial}} - f_{\min}}{f_{\max} - f_{\min}} - \text{ if } f_{\max} \text{ is the worst value,} \end{cases} \tag{1}$$

where f_{norm} is the normalized result, f_{initial} the initial value, and $f_{\max}$ and $f_{\min}$ are the maximum and minimum values of this parameter.

By this approach, the normalized data can be interpreted in equal terms. For each parameter, 0 is the worst result and 1 is the best result.

4. HIGH-SPEED ELECTRICAL MACHINE MATERIALS

4.1. Assessment of the Stator Material

The methods introduced in this paper are demonstrated for the selection of the stator lamination material. The most commonly used lamination materials in high-speed machines are selected for comparison, namely M270-50A, M270-35A, NO27, NO20, NO10, and a more rare 10JNEX900 lamination. Ten lamination suppliers were requested for a quotation for the same prototype geometry and alternative materials available. Based on the quotations, the relative costs and availability of the materials are obtained. These parameters are given in Table 1. The other important parameters are obtained from the manufacturers' datasheets [32, 33]. These parameters include the relative losses at 400 Hz and 2500 Hz at 1 T. The space factor depends on the lamination and insulation thickness and has an impact on the core losses. The relative values of this parameter are listed according to [34, 35] in Table 1. The value of the flux density at which the flux density saturation occurs at 50 Hz is shown with the relative parameter saturation. The relative resistivity and yield strength of the lamination materials are also presented. The data are normalized using (1).

Table 1. Normalized parameters of the stator lamination material.

Material	Price	Availability	Loss at 400 Hz	Loss at 2500 Hz	Space factor	Saturation	Resistivity	Yield strength
M270-50A	1	1	0	0	1	0.22	0.64	0.33
M270-35A	0.89	0.88	0.39	0.52	0.86	0.11	0.64	0.26
NO27	0.78	0.63	0.57	0.70	0.57	0	1	0.19
NO20	0.72	0.38	0.66	0.80	0.29	0.78	0.36	0
NO10	0.61	0.25	0.66	0.96	0	0	0.36	0
10JNEX900	0	0	1	1	0	1	0	1

Table 2. Comparison matrix of the stator lamination material parameters.

Parameters	Price	Availability	Loss at 400 Hz	Loss at 2500 Hz	Space factor	Saturation	Resistivity	Yield strength
Price	1	2	1	2	3	4	4	6
Availability	1/2	1	1	2	3	3	2	4
Loss at 400 Hz	1	1	1	3	2	3	3	5
Loss at 2500 Hz	1/2	1/2	1/3	1	1/2	1	1/4	2
Fill factor	1/3	1/3	1/2	2	1	2	1/4	2
Saturation	1/4	1/3	1/3	1	1/2	1	1/4	1
Resistivity	1/4	1/2	1/3	4	4	4	1	4
Yield strength	1/6	1/4	1/5	1/2	1/2	1	1/4	1

Table 3. Weight coefficients of the stator lamination material parameters.

Parameters	Weight coefficient	Parameter rank
Price	0.253	1
Availability	0.169	3
Loss at 400 Hz	0.204	2
Loss at 2500 Hz	0.063	6
Fill factor	0.077	5
Saturation	0.048	7
Resistivity	0.148	4
Yield strength	0.037	8

Table 4. Ranking results of the stator lamination material.

Parameters	Ranking factor	Rank
M270-50A	0.616	3
M270-35A	0.621	2
NO27	0.622	1
NO20	0.564	4
NO10	0.434	5
10JNEX900	0.425	6

After the data normalization, the AHP method starts the pairwise comparison of the material properties. The importance of price in the material selection is compared first with availability, then with losses at 400 Hz, and with all other properties. For example, in Table 2, a judgment is made that for an HS machine, the material price is twice as important as availability (thus the value 2 in the table cell). The relative importance of one parameter over another is expressed. The same procedure is applied for all material parameters. All the judgments constitute an $n \times n$ pairwise comparison matrix, where the main diagonal elements equal 1 and $a_{ij} = 1/a_{ji}$ for all $i, j = 1, \ldots, n$. An example of the comparison matrix for the lamination parameters is shown in Table 2.

The next step is the conversion of the comparison matrix in Table 2 into weight coefficients for every parameter. For this purpose, an eigenvector is calculated. The values of the eigenvector are the relative weight coefficients of the parameters. The weight coefficients and ranks of the lamination material parameters are given in Table 3. According to the results, price, loss at 400 Hz, and availability are the most important parameters for the selected operating frequencies.

The final step is scoring of the results based on the data of Tables 2 and 3. The resulting ranking factors RF are calculated by the following equation

$$\mathrm{RF} = \sum_{i=1}^{n} f_i w_i, \tag{2}$$

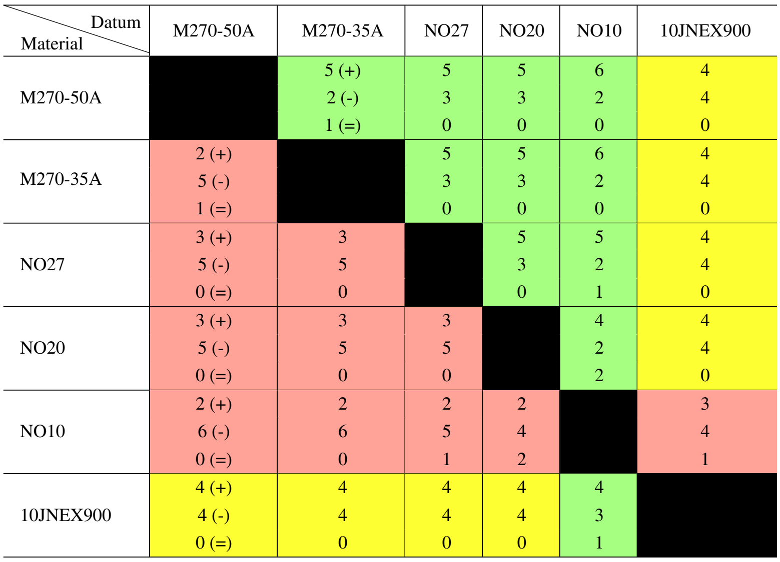
where f_i are the material normalized parameters and w_i the weight coefficients of the parameters. The calculated ranking factors and the ranks for the lamination materials are given in Table 4. The results show that NO27, M270-35A, and M270-50A are the first options for the design. These materials have an acceptable per unit loss level at 400 Hz and a low price, and are usually available in stock according to the data of Table 1.

Sometimes in the design process there is a need to select between two lamination material options. A pairwise comparison applying the Pugh matrix allows to choose one out of two materials based on their parameters. The method has three steps. First, one option is selected and assigned as a basis or "datum" for the comparison. The second step is the comparison of the parameters of the options with

Table 5. Comparison of the Datum material NO20 and M270-50A.

Parameters	NO20	M270-50A	Result
Price	0.72	1	better than datum (+)
Availability	0.25	1	better than datum (+)
Loss at 400 Hz	0.66	0	worse than datum (−)
Loss at 2500 Hz	0.8	0	worse than datum (−)
Fill factor	0.29	1	better than datum (+)
Knee	0.78	0.22	worse than datum (−)
Resistivity	0.36	0.64	better than datum (+)
Yield strength	0	0.33	better than datum (+)

Table 6. Pugh matrix for the stator lamination material.



Datum Material	M270-50A	M270-35A	NO27	NO20	NO10	10JNEX900
M270-50A		5 (+) 2 (-) 1 (=)	5 3 0	5 3 0	6 2 0	4 4 0
M270-35A	2 (+) 5 (-) 1 (=)		5 3 0	5 3 0	6 2 0	4 4 0
NO27	3 (+) 5 (-) 0 (=)	3 5 0		5 3 0	5 2 1	4 4 0
NO20	3 (+) 5 (-) 0 (=)	3 5 0	3 5 0		4 2 2	4 4 0
NO10	2 (+) 6 (-) 0 (=)	2 6 0	2 5 1	2 4 2		3 4 1
10JNEX900	4 (+) 4 (-) 0 (=)	4 4 0	4 4 0	4 4 0	4 3 1	

a datum. Finally, the next option is assigned as a datum, and the procedure is repeated.

For example, the material NO20 is assigned as a datum and compared with M270-50A. The results of the comparison are shown in Table 5. The pairwise comparison shows that M270-50A has five parameters that are better than the datum, and three parameters that are worse than the datum. According to the Pugh method, the material M270-50A is a better option than NO20. This is also confirmed by the AHP analysis, where M270-50A has a rank of 3 and NO20 has a rank of 4.

Table 6 shows the results of the pairwise material comparison based on the Pugh method. The rows represent the selected materials, which are compared with respect to the datum, and the columns represent the datum. In each cell, the top value indicates the number of parameters that are better than the datum, the middle value is the number of parameters that are worse than the datum, and the bottom value is the number of parameters of equal value. If the selected material is better than the datum, the cell is highlighted in green, if it is worse than the datum, the cell is highlighted in red, and if the materials are equal, the cell is highlighted in yellow.

The drawback of the Pugh method is the equal assessment of all option parameters. Therefore, less important parameters, for instance, lamination yield strength, may affect the results of the pairwise comparison. It can be seen in Table 6 that by applying the Pugh method it is difficult to compare materials that have very distinct parameters, for example, 10JNEX900. Therefore, the Pugh method is suitable for the comparison of options that have similar parameters.

When assessing the lamination materials by the two methods described above, it can be seen that the price difference is not critical in the case of the M-series and NO-series steels; however, the availability of these series is usually an issue. In many cases, NO20 and higher grades have to be purchased separately. Because of the exceptional characteristics of the 10JNEX900, this material has the lowest per unit losses at high frequencies among silicon-iron (SiFe) alloys [33]. The high price and low availability of this material makes it a favorable choice only in very demanding applications.

4.2. Assessment of the Rotor Sleeve Material

The rotor sleeve material significantly affects the maximum power and rotational speed of the proposed HS machine topology. The electromagnetic, mechanical, and thermal factors are acting simultaneously on the retaining sleeve. The common rotor retaining sleeve materials used in HS PMSMs and their normalized properties are given in Table 7. The materials prices and availability are obtained by the same procedure as with the stator lamination. The yield strength, density, thermal conductivity, and resistivity of the sleeve materials are found in [36–38].

Similar to the stator lamination AHP analysis, a comparison matrix is produced for the rotor lamination materials. The comparison matrix of the material parameters is shown in Table 8. The eigenvector of this matrix provides information about the relative importance of each parameter. The weight coefficients of the rotor retaining sleeve material parameters are shown in Table 9.

The yield strength and density of the material determine the maximum rotational speed, while resistivity defines the losses in the retaining sleeve. Therefore, these parameters are of a high importance. A high yield strength allows higher rotational speeds than a low material density, which is shown in Table 8 with the value of 5. The price and availability of the materials should also be taken into account in the selection of the rotor sleeve material.

According to the AHP method results presented in Table 10, the titanium retaining sleeve is the best compromise between cost and performance. Stainless steel or carbon fiber retaining sleeves are the next best options depending on the stresses occurring in the sleeve material.

Table 7. Normalized parameters of the rotor retaining sleeve material.

Material	Price	Availability	Yield strength	Density	Thermal conductivity	Resistivity
ANSI 316L	1	1	0	0.03	1	0
Ti6Al4V	0.64	0.43	0.75	0.59	0.38	0.04
Inconel 718	0	0	1	0	0.69	0.02
Carbon fiber	0.21	0	0.66	1	0	1

Table 8. Comparison matrix of the rotor retaining sleeve material parameters.

Parameters	Price	Availability	Yield strength	Density	Thermal conductivity	Resistivity
Price	1	2	1/2	3	2	1
Availability	1/2	1	1/3	3	2	3/2
Yield strength	2	3	1	5	5/2	2
Density	1/3	1/3	1/5	1	1/3	1/5
Thermal conductivity	1/2	1/2	2/5	3	1	1/2
Resistivity	1	2/3	1/2	5	2	1

Table 9. Weight coefficients of the rotor retaining sleeve material parameters.

Parameters	Weight coefficient	Parameter rank
Price	0.192	2
Availability	0.157	4
Yield strength	0.326	1
Density	0.048	6
Thermal conductivity	0.103	5
Resistivity	0.174	3

Table 10. Ranking results of the rotor retaining sleeve material.

Material	Ranking factor	Rank
ANSI 316L	0.45	2
Ti6Al4V	0.51	1
Inconel 718	0.34	4
Carbon fiber	0.44	3

Table 11. Pugh matrix for the rotor retaining sleeve material.

Datum Material	ANSI 316L	Ti6AI4V	Inconel 718	Carbon fiber
ANSI 316L	■	3 (+) 3 (-) 0 (=)	4 2 0	3 3 0
Ti6AI4V	3 (+) 3 (-) 0 (=)	■	4 2 0	4 2 0
Inconel 718	2 (+) 4 (-) 0 (=)	2 4 0	■	2 4 0
Carbon fiber	3 (+) 3 (-) 0 (=)	2 4 0	4 2 0	■

Table 11 shows the Pugh matrix for the retaining sleeve materials. The data are obtained applying the principle explained in Table 5. In line with the AHP method results, the Pugh matrix demonstrates that Inconel is the least favorable option because of its high price.

The suggested stainless steel grades are the lowest-cost options, and these materials have the lowest yield strengths and the highest conductivities compared with the other sleeve materials. The implementation of titanium, Inconel, or carbon fiber significantly extends the boundaries of the machine with the proposed topology but also the material price rises. Carbon fiber has exceptional yield strength and resistivity but its thermal conductivity is very low. In the proposed construction, this is critical because the only rotor cooling channel is the outer surface of the sleeve. In this case, the carbon fiber can only be selected with permanent magnets of high temperature grade.

5. PROTOTYPE VALIDATION

Based on the results of the material analysis, two prototypes with the proposed topology were built and optimized. The first one is a 3.5 kW, 45 000 rpm PMSM for a turbo blower. The second one is an 11 kW, 31 200 rpm permanent magnet synchronous generator for a micro Organic Rankine Cycle (ORC) power plant.

In the 3.5 kW machine, NO10 lamination and a titanium retaining sleeve were used. These materials were chosen to significantly extend the speed and power limits and ensure stable operation of the first prototype. The other design methods implemented in the machine were installation of magnetic wedges and selection of the bearing solution.

Another approach to the electrical machine design was taken in the 11 kW generator. The materials chosen for the second prototype were M-270-35A lamination and an ANSI 316L retaining sleeve. According to Tables 4 and 10, these materials are preferable solutions. The methods applied in the design process are optimization of the air gap length, yoke thickness, and tooth tip, and installation of a magnetic wedge. As a result, the performance of the 11 kW machine is relatively similar to the 3.5 kW machine but with lower costs and manufacturing time.

The prototype test results show a good correlation between the simulated and measured losses. More detailed information of the prototypes and testing can be found in [39].

6. CONCLUSION

In this paper, an assessment of the lamination and rotor sleeve materials for a 2-pole, 6-slot HS PMSM with tooth-coil windings is presented. The materials are assessed applying the AHP and Pugh matrix methods. The rank results of the AHP assessment are presented in tables. The Pugh matrix allows a pairwise comparison of the selected materials for high-speed electrical machines.

Two prototypes demonstrate alternative strategies for the HS machine design. In the 3.5 kW machine, expensive materials are used to extend the power and speed limits of the machine. In the case of the 11 kW machine, only the materials with the highest assessment ranks are applied to the design.

REFERENCES

1. Chau, K.-T., W. Li, and C. H. T. Lee, “Challenges and opportunities of electric machines for renewable energy,” *Progress In Electromagnetics Research B*, Vol. 42, 45–74, 2012.
2. Misron, N. B., S. Rizuan, R. N. Firdaus, C. Aravind Vaithilingam, H. Wakiwaka, and M. Nirei, “Comparative evaluation on power-speed density of portable permanent magnet generators for agricultural application,” *Progress In Electromagnetics Research*, Vol. 129, 345–363, 2012.
3. Gerada, D., A. Mebarki, N. Brown, C. Gerada, A. Cavagnino, and A. Boglietti, “High-speed electrical machines: Technologies, trends, and developments,” *IEEE Transactions on Industrial Electronics*, Vol. 61, No. 6, 2946–2959, Jun. 2014.
4. Pyrhönen, J., J. Nerg, P. Kurronen, and U. Lauber, “High-speed high-output solid-rotor induction-motor technology for gas compression,” *IEEE Transactions on Industrial Electronics*, Vol. 57, No. 1, 272–280, Jan. 2010.
5. Touati, S., R. Ibtiouen, O. Touhami, and A. Djerdir, “Experimental investigation and optimization of permanent magnet motor based on coupling boundary element method with permeances network,” *Progress In Electromagnetics Research*, Vol. 111, 71–90, 2011.
6. Riemer, B., M. Lessmann, and K. Hameyer, “Rotor design of a high-speed permanent magnet synchronous machine rating 100,000 rpm at 10 kw,” *Proc. IEEE ECCE*, 3978–3985, Sep. 2010.
7. Jiang, W. and T. Jahns, “Coupled electromagnetic-thermal analysis of electric machines including transient operation based on finite-element techniques,” *IEEE Transactions on Industry Applications*, Vol. 51, No. 2, 1880–1889, Mar. 2015.
8. Pesch, A., A. Smirnov, O. Pyrhönen, and J. Sawicki, “Magnetic bearing spindle tool tracking through m-synthesis robust control,” *IEEE ASME Transactions on Mechatronics*, Vol. 20, No. 3, 1448–1457, Jun. 2015.

9. Bianchi, N., S. Bolognani, and F. Luise, "Potentials and limits of high-speed PM motors," *IEEE Transactions on Industry Applications*, Vol. 40, No. 6, 1570–1578, Nov. 2004.
10. Kolondzovski, Z., A. Arkkio, J. Larjola, and P. Sallinen, "Power limits of high-speed permanent-magnet electrical machines for compressor applications," *IEEE Transactions on Energy Conversion*, Vol. 26, No. 1, 73–82, Mar. 2011.
11. Chen, M., K.-T. Chau, C. H. T. Lee, and C. Liu, "Design and analysis of a new axial-field magnetic variable gear using pole-changing permanent magnets," *Progress In Electromagnetics Research*, Vol. 153, 23–32, 2015.
12. Uzhegov, N., J. Pyrhönen, and S. Shirinskii, "Loss minimization in high-speed permanent magnet synchronous machines with tooth-coil windings," *Proc. IEEE IECON*, 2960–2965, Nov. 2013.
13. Xu, G., L. Jian, W. Gong, and W. Zhao, "Quantitative comparison of flux-modulated interior permanent magnet machines with distributed and concentrated windings," *Progress In Electromagnetics Research*, Vol. 129, 109–123, 2012.
14. Lim, M.-S., S.-H. Chai, J.-S. Yang, and J.-P. Hong, "Design and verification of 150-krpm pmsm based on experiment results of prototype," *IEEE Transactions on Industrial Electronics*, Vol. 62, No. 12, 7827–7836, Dec. 2015.
15. Salonen, M. and M. Perttula, "Utilization of concept selection methods: A survey of finnish industry," *Proc. ASME IDETC/CIE*, 527–535, Sep. 2005.
16. Pyrhönen, J., V. Ruuskanen, J. Nerg, J. Puranen, and H. Jussila, "Permanent-magnet length effects in AC machines," *IEEE Transactions on Magnetics*, Vol. 46, No. 10, 3783–3789, Oct. 2010.
17. Uzhegov, N., J. Nerg, and J. Pyrhönen, "Design of 6-slot 2-pole high-speed permanent magnet synchronous machines with tooth-coil windings," *Proc. XXIst ICEM*, 2537–2542, Sep. 2014.
18. Borisavljevic, A., H. Polinder, and J. Ferreira, "On the speed limits of permanent-magnet machines," *IEEE Transactions on Industrial Electronics*, Vol. 57, No. 1, 220–227, Jan. 2010.
19. Zhao, W., M. Cheng, R. Cao, and J. Ji, "Experimental comparison of remedial single-channel operations for redundant flux-switching permanent-magnet motor drive," *Progress In Electromagnetics Research*, Vol. 123, 189–204, 2012.
20. Binder, A. and T. Schneider, "High-speed inverter-fed ac drives," *Proc. ACEMP'07 Int. Aegean Conf.*, 9–16, Sep. 2007.
21. Pugh, S., *Creating Innovative Products Using Total Design: The Living Legacy of Stuart Pugh*, edited by D. Clausing and R. Andrade, Addison-Wesley, New York, 1996.
22. Saaty, T. L., *The Analytic Hierarchy Process*, McGraw-Hill, New York, 1980.
23. Matzen, M., M. Alhajji, and Y. Demirel, "Chemical storage of wind energy by renewable methanol production: Feasibility analysis using a multi-criteria decision matrix," *Energy*, Vol. 93, 343–353, 2015.
24. Girones, V., S. Moret, F. Marechal, and D. Favrat, "Strategic energy planning for large-scale energy systems: A modelling framework to aid decision-making," *Energy*, Vol. 90, 173–186, 2015.
25. Thakker, A., J. Jarvis, M. Buggy, and A. Sahed, "3dcad conceptual design of the next-generation impulse turbine using the pugh decision-matrix," *Materials and Design*, Vol. 30, No. 7, 2676–2684, 2009.
26. Ullman, D. G., *The Mechanical Design Process*, McGraw-Hill, New York, 2010.
27. Okudan, G. and S. Tauhid, "Concept selection methods — A literature review from 1980 to 2008," *International Journal of Design Engineering*, Vol. 1, No. 3, 243–277, 2008.
28. Nasiri-Zarandi, R., M. Mirsalim, and A. Cavagnino, "Analysis, optimization, and prototyping of a brushless dc limited-angle torque-motor with segmented rotor pole tip structure," *IEEE Transactions on Industrial Electronics*, Vol. 62, No. 8, 4985–4993, Aug. 2015.
29. Dziadak, B. and A. Michalski, "Evaluation of the hardware for a mobile measurement station," *IEEE Transactions on Industrial Electronics*, Vol. 58, No. 7, 2627–2635, Jul. 2011.
30. Meyar-Naimi, H. and S. Vaez-ZAdeh, "Sustainability assessment of a power generation system using dsr-hns framework," *IEEE Transactions on Energy Conversion*, Vol. 28, No. 2, 327–334, Jun. 2013.

31. Chedid, R., H. Akiki, and S. Rahman, "A decision support technique for the design of hybrid solar-wind power systems," *IEEE Transactions on Energy Conversion*, Vol. 13, No. 1, 76–83, Mar. 1998.
32. Cogent, "Non-oriented electrical steel," [Online]. Available: http://cogent-power.com/, 2016.
33. Senda, K., M. Namikawa, and Y. Hayakawa, "Electrical steels for advanced automobiles — Core materials for motors, generators, and high-frequency reactors," *JFE Technical Report*, No. 4, 67–73, 2004.
34. Tarter, R. E., *Solid-state Power Conversion Handbook*, John Wiley & Sons, New York, NY, 1993.
35. Nasar, S. A. and L. E. Unnewehr, *Electromechanics and Electric Machines*, JohnWiley & Sons, New York, 1979.
36. Kolondzovski, Z., A. Belahcen, and A. Arkkio, "Comparative thermal analysis of different rotor types for a high-speed permanent-magnet electrical machine," *IET Electric Power Applications*, Vol. 3, No. 4, 279–288, Jul. 2009.
37. Clemens, S. L. and W. C. Faulkner, *Engineered Materials Handbook*, ASM, Metals Park OH, 1991.
38. Yon, J., P. Mellor, R. Wrobel, J. Booker, and S. Burrow, "Analysis of semipermeable containment sleeve technology for high-speed permanent magnet machines," *IEEE Transactions on Energy Conversion*, Vol. 27, No. 3, 646–653, Sep. 2012.
39. Uzhegov, N., E. Kurvinen, J. Nerg, J. Pyrhönen, J. Sopanen, and S. Shirinskii, "Multidisciplinary design process of a 6-slot 2-pole high-speed permanent-magnet synchronous machine," *IEEE Transactions on Industrial Electronics*, Vol. 63, No. 2, 784–795, Feb. 2016.

Publication VI

Luuka, P., Efimov-Soini N., Collan M. and Kozlova, M.
Fuzzy MCDM-procedure for Design Evaluation: Capturing Redundant Information with an Interaction Matrix.
Reprinted with permission from
Journal of multiple-valued logic & soft computing
vol. 29, pp. 469-484., 2017

J. of Mult.-Valued Logic & Soft Computing, Vol. 29, pp. 469–484
Reprints available directly from the publisher
Photocopying permitted by license only

Fuzzy MCDM-procedure for Design Evaluation: Capturing Redundant Information with an Interaction Matrix

PASI LUUKKA, NIKOLAI EFIMOV-SOINI, MIKAEL COLLAN
AND MARIIA KOZLOVA

Lappeenranta University of Technology, School of Business and Management,
Skinnarilankatu 34, 53850 Lappeenranta, Finland

Accepted: August 26, 2016.

Design choices made early in the product development process have an important impact on the chances of product commercialization and on product success in general. These choices are typically multiple-criteria problems, where estimates about the goodness of each criterion often contain overlapping redundant information. Many multiple-criteria decision-making methods that can support design selection exist, but there are very few methods out there that properly consider interdependent criteria and information redundancy. This paper proposes a new MCDM procedure for design evaluation that is able to capture overlapping information through a simple interaction matrix and weight-formation for each criterion that is based on the degree of their interaction. The use of the proposed procedure is numerically illustrated with a case study.

Keywords: MCDM, interacting variables, information redundancy, design choice

1 INTRODUCTION

Design evaluation is an important part of what is typically called the conceptual design stage of product development processes, where the design or designs that go forward in the design process are chosen. The conceptual design stage influences the outcome of the product design process and will often also determine the whole product life-cycle. An unfortunate concept choice may complicate the manufacturing and the commercialization of the end-product. Moreover, it is well-known that the further in the product development process a concept is revised, the more the revision will be likely to cost [1]. Design evaluation is a task that involves the evaluation of “goodness” of designs and is based on multiple criteria that may be interacting. By interacting criteria we mean a situation, where the evaluations of separate criteria may partially carry the same information and where by definition there is information overlap or redundancy. Furthermore, the evaluations are not necessarily precisely measurable, but they are often imprecise normative judgments that often come from multiple evaluators. For elicitation of the normative judgments it is not uncommon that linguistic scales are used.

At present, there are several methods in use for design evaluation [2] these include the Analytic Hierarchy Process (AHP) [3], the Pugh matrix [4], and Quality Function Deployment (QFD) [5]. AHP is one of the most used methods in industry for design evaluation and selection [9, 10]. The AHP consists of two main phases, the construction of a hierarchy of criteria and of the evaluation of alternatives that is based on pair-wise comparison by a group of experts. Human judgment is central in the AHP, but the process does not explicitly capture information redundancy.

The Pugh matrix is a simple tool that is commonly used in design evaluation that is based on pair-wise comparison of alternatives to a “baseline” alternative (one of the competing designs is chosen as the baseline alternative) on a criteria-by-criteria basis. In the simplest form of the tool, the comparison is done in terms of three alternative states that are “better than $(+)$”, “worse than $(-)$”, and “same as (0)” the baseline alternative. The tool works simply by adding the “plusses, zeroes, and the minuses” to see which design has the highest positive result overall. The method has been applied to the design selection problem, e.g., in energy engineering [11, 12] and in mechanical design [13]. The Pugh matrix can and has been integrated with other methods, such as the QFD [5], which is a technique used to transform customer needs into engineering characteristics.

Generally speaking, multiple-criteria decision-making modeling can be divided into four families of methods [24], where the first is based on utility theory approach started by Keeney and Raiffa [31] and from which, e.g., the AHP [3] is one good example. The second one is the “outranking methods”, based on the seminal work by Bernard Roy [27] and of which methods like Electre [27] and Promethee [28] are among the most widely applied. The third family is the so called “group decision and negotiation theory”-based methods (see, e.g., [29]) and the fourth group are the “interactive multiple objective programming approaches” (see, e.g. [30]). It is likely that many methods from within these families can be applied in design evaluation. It is typical that the available methods assume the evaluated criteria to be (fully) independent.

As discussed above, the evaluations for the different criteria used in design evaluation can be normative and imprecise. Fuzzy sets and fuzzy logic, proposed by Zadeh in 1965 [22] are a widely accepted methodology for the treatment of imprecision that is also usable in the decision-making modeling [23]. Many fuzzy variants of MCDM methods exist that are able to treat normative imprecise information [24-26]. There is some previous research on including the interdependencies of criteria into fuzzy multiple-criteria decision-making by using linear programming [18-20] and in connection with information aggregation [7, 21].

In this vein we propose a new design evaluation method that is able to treat imprecise multiple-criteria evaluations in a situation, where criteria can be interacting in terms of containing overlapping redundant information. For the purpose of capturing the interaction between the criteria, we resort to using an interaction matrix that bears some similarity to the afore-mentioned Pugh matrix that is commonly used in design evaluation. The interaction matrix is used to form weights that represent the amount of redundant information contained within each criterion and that can be used in the aggregation of the evaluations.

The new procedure brings clear improvement over the previously in design evaluation used methods, because of the ability to consider information redundancy. For instance, to put the benefit into a real-world context, the "cost" of a design of a product is essentially linked to its quality characteristics, such as lifetime and/or productivity - embedding these into a design evaluation as independent criteria can contaminate the results and bias decision making.

The application of the proposed procedure is presented with a simple case of evaluating three flow-meter designs, an electromagnetic, a turbine-based, and an ultrasonic flow-meter. The engineering features (criteria to be evaluated) of the designs are represented with fuzzy numbers to capture the imprecision found in the estimates.

The rest of the paper is structured as follows: the second section provides the mathematical background for and the description of the proposed MCDM procedure. The third section describes the numerical case study and demonstrates how the proposed procedure is applied. Finally, the paper is closed with some concluding remarks.

2 THE PROPOSED MCDM PROCEDURE FOR DESIGN EVALUATION

2.1 Mathematical background

In this section the mathematical and methodological background needed is presented. We present the definition used for triangular fuzzy numbers and for fuzzy heavy weighted averaging (FHWA) operator and present the ranking procedure used for ordering fuzzy numbers.

Definition 1. *A triangular fuzzy number* $\hat{a}$ *can be defined by a triplet* $\hat{a} = (a_1, a_2, a_3)$. *The membership function* $\mu_{\hat{a}}(x)$ *is defined as [8].*

$$\mu_{\hat{a}}(x) = \begin{cases} 0, & x < a_1 \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 \le x \le a_2 \\ \dfrac{x - a_3}{a_2 - a_3}, & a_2 \le x \le a_3 \\ 0, & x > a_3 \end{cases} \tag{1}$$

For arithmetic operations for triangular fuzzy numbers we refer to [8]. Next we turn to presenting the aggregation operator used in the proposed procedure and present the definition for the Fuzzy Heavy Weighted Averaging (FHWA) operator [7].

Definition 2. *Let U be the set of fuzzy numbers. A Fuzzy Heavy Weighted Averaging (FHWA) operator of dimension n is a mapping FHWA:* $U^n \rightarrow U$ *that has an associated weighting vector W of dimension* n, *such that the sum of the weights is between* $[1, n]$ *and* $w_i \in [0,1]$, *then:*

$$FHWA(\hat{a}_1, \hat{a}_2, \cdots, \hat{a}_n) = \sum_{i=1}^{n} w_i \hat{a}_i \tag{2}$$

where $(\hat{a}_1, \hat{a}_2, \cdots, \hat{a}_n)$, *are fuzzy triangular numbers of the form given in definition 1.*

For the ranking of the (from the evaluation process) resulting fuzzy numbers that represent the goodness of each evaluated alternative, we use the method introduced by Kaufmann and Gupta [8]. The method ranks fuzzy numbers according to a three-step process, where three ranking criteria are used in hierarchical manner – if the first used criterion does not give a unique ordering, then the second criterion is used, and if a unique ordering is still not reached, then a third criterion is applied. The the three criteria are:

(i) "Removal number with respect to k": $R(\hat{a}, k) = \frac{1}{2}(R_l(\hat{a}, k) + R_r(\hat{a}, k))$. In the case that k is selected to be the origo ($k = 0$), the removal value computations for triangular fuzzy number result as:

$$R_l(\hat{a}, k = 0) = a_2 - \int_{a_1}^{a_2} dx,\ R_r(\hat{a}, k = 0) = a_2 + \int_{a_2}^{a_3} dx$$

(ii) "Mode": mode is calculated for all fuzzy numbers, for which unique ordering has not been found. The modes will generate sub-classes that allow ranking, in case some fuzzy numbers under consideration have non-unique modes, one can take the mean position of the modal values. For mode, the usual choice is the core value of the fuzzy number $Mode\,(\hat{a}) = \{x \in U \,|\hat{a}\,(x) = 1|\}$. Mode in the case of triangular fuzzy number reduces to $Mode(A) = a_2$.

(iii) "Divergence" is used, if the previous two criteria fail to return a unique ordering of the numbers. If we consider, the divergence around the mode for each fuzzy number for each sub-class with multiple fuzzy numbers we obtain sub-sub-classes. This criterion may be sufficient to obtain the final ordering of the fuzzy numbers.
$Divergence\,(\hat{a}) = supp_{x\in U}\,(supp\,(\hat{a})) - \inf_{x\in U}\,(supp\,(\hat{a}))\,,$ where $supp\,(\hat{a}) = \{x \in U \,|\hat{a}\,(x) > 0|\}$. Divergence in the case of triangular number reduces to *Divergence(A)*$= (a_3 - a_1)$.

In the next section we present the interaction matrix used to elicit information about the overlapping information contained in the used criteria and how it can be used in the formation of criteria weights for the aggregation of the overall figure that is used to describe design "goodness".

2.2 Interaction-weight formation and the interaction matrix

In this paper we consider weights as representations of interaction in terms of information redundancy between different criteria. Interaction between criteria can be understood to take place in two different forms, as redundancy and as synergy, where redundancy refers to a situation, where the same information is contained in two or more criteria and there is "overlap" of the same information, and where synergy refers to a situation where the added value of two pieces of information together reveals more than their individual values together and there is "revealed" new information that can be gained.

Of these forms redundancy was addressed by Yager in 2002 [21] in connection with weighting vectors that bear redundant information and he proposed the following expression to measure redundancy ρ in a weighting vector w.

$$\rho = \frac{n - |w|}{n - 1} \tag{3}$$

where $|w|$ denotes the cardinality of the weighting vector w, and where n is the number of elements in the vector. With this weighting scheme the weight $w = [1, 1]$ gives a redundancy of $\rho = 0$ *(no redundancy)* and the situation is that with a totaling operator and in the other extreme with a weighted averaging operator, where the weight $w = [1 - \alpha, \alpha]$ the redundancy is $\rho = 1$ *(total* *redundancy)*. Partial redundancy can be achieved with weights between the above minima and maxima weights.

A measure for synergy, S, for synergy in a weighting vector was proposed by Collan and Luukka [7]:

$$S = \frac{|w| - n}{n - 1} \tag{4}$$

In this expression the synergy value moves from negative through zero to positive, where negative values indicate redundancy, zero synergy indicating independent criteria, and where positive values indicate the existence of synergy.

Next, we go into how the interaction matrix can be used to form a weighting vector w that bears the information regarding the redundancy of the interacting criteria. After the interaction matrix containing all the used criteria is constructed, the interaction between criteria is evaluated. Interaction evaluation can be done by experts in a way that each criterion's interaction with other criteria is specifically evaluated and estimated. This can also be done simply by considering that only two states of interaction, "interaction" (1), or "no interaction" (0) exist – this simplicity is in vein with the Pugh matrix, with which many design engineers are used to working. From these evaluations an "interaction vector" is created. Consider an interaction matrix as

$$Y = \left(y_{ij}\right)_{n \times n} \tag{5}$$

where $y_{ij} \in \{0,1\}$ denotes the presence / absence of interaction. We also assume $y_{ii} = 0$, meaning that a variable will not interact with itself. In case expert information exists, then $y_{ij} \in [0,1]$. The interaction vector is created by calculating the cardinality of interactions present for different criteria.

$$I_j = \sum_{i=1}^{n} y_{ij} \tag{6}$$

A scaling to the unit interval is done

$$\widehat{I}_j = \frac{I_j}{I_{max}} \tag{7}$$

where $I_{max} = n$ denotes the maximum possible interaction for a criterion. From this interaction vector one can form the interaction weights by taking the complement of the interaction vector.

$$w_j = 1 - \hat{I}_j \tag{8}$$

The obtained weights are used in the aggregation step of the MCDM procedure performed with the fuzzy heavy weighted average.

2.3 The used fuzzy MCDM procedure

The following general situation is considered, where a finite set of alternatives $A = \{A_i | i = 1, \cdots, m\}$ needs to be evaluated by considering a finite set of given criteria $C = \left\{C_j | j = 1,2, \ldots, n\right\}$. A decision matrix representation of the performance evaluation of each alternative A$_i$is considered, with respect to each criterion C_j as follows:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{9}$$

where m rows represent m possible candidates, n columns represent n relevant criteria, and x_{ij} represents the performance rating of the i-th alternative, with respect to the j-th criterion C_j. These ratings are evaluated by using triangular fuzzy numbers.

The decision matrix is put to go through a linear scale transformation to transform the various criteria scales into comparable units. The criteria set can be divided into benefit criteria (larger the rating, the greater the preference) and into cost criteria (the smaller the rating, the greater the preference). The normalized fuzzy decision matrix can be represented as:

$$R = \left(r_{ij}\right)_{m \times n} \tag{10}$$

Normalization is performed as follows:

$$r_{ij} = \left(\frac{a_{ij}}{c_j^{\oplus}}, \frac{b_{ij}}{c_j^{\oplus}}, \frac{c_{ij}}{c_j^{\oplus}}\right) \tag{11}$$

where $c_j^{\oplus} = max_i\left(U_i\right)$, where U_i is considered to be a positive real and the maximum for U_i is either expert defined, or derived from the available data. The transformation into a comparable scale is done by using a complement for all the cost criteria

$$r_{ij} = \left(1 - \frac{c_{ij}}{c_j^{\oplus}}, 1 - \frac{b_{ij}}{c_j^{\oplus}}, 1 - \frac{a_{ij}}{c_j^{\oplus}}\right) j \in C \tag{12}$$

where $j \in C$ denotes that criterion j is cost criterion. If $j \notin C$ we simply use equation (11).

This normalized decision matrix is aggregated with regards to the criteria by using the fuzzy heavy weighted averaging operator (FHWA).

$$R_i = FHWA(r_{i1}, r_{i2}, \cdots, r_{in}) = \sum_{j=1}^{n} w_j r_{ij} \tag{13}$$

where $w_j \in [0,1]$ and $\sum_{j=1}^{n} w_j \in [1, n]$ and w_j is computed from the interaction matrix Y.

At this point we have *m* different fuzzy numbers that represent the overall "goodness" of the compared design alternatives that need to be ranked in order to get a final order of goodness. This is done by ranking R_i according to method introduced by Kaufmann & Gupta [8] explained above. The outline of the proposed method has been previously presented in [6].

3 NUMERICAL CASE ILLUSTRATION

3.1 Case description

The background of the case is evaluation of flow-meter designs, flow-meters evaluated here are devices used in the measurement of the flow of liquids through pipes that can be used in various instances, e.g., in buildings, oil-pumps, nuclear reactors etc. There various types of flow-meters that have been constructed by using different technological bases, e.g., ultrasonic, electromagnetic, turbine-based, coriolis-effect-based and so on. In different design projects the choice of the flow-meter used typically depends on several characteristics attached to the design of flow-meters. In this illustration we focus on three different flow-meter designs electromagnetic, turbine-based, and ultrasonic. The alternatives are evaluated based on nine criteria: "cost", "working time", "consumption", "flow-rate at specified accuracy", "sortiment of different liquids that the meter works with", "ease of installation", "processing of the electronic signal", "shelf-time", and "installation cost". It is well-known that information redundancy is present within the nine criteria and many of the criteria cannot be precisely estimated by measurement and the information will come from experts in the form of fuzzy number estimates. Next the three different flow-meters are briefly introduced for reference.

3.1.1 Electromagnetic flow-meter

The electromagnetic (EM) flow meter (Figure 2) is typically used for designs, e.g., in heating, air conditioning, water supply and treatment, and drinking water distribution systems [14]. The main feature of the electromagnetic flow-meter is its ability to work with any conducive liquid.

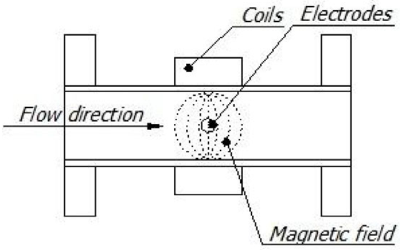


FIGURE 1
Electromagnetic flow-meter

In the EM flow-meter the electric signal that drives the metering is generated by a magnetic field that originates from coil interaction with the passing liquid (see Figure 1). The signal is typically processed by a controller unit.

3.1.2 Turbine-based flow-meter

The turbine-based flow-meter design (Figure 2) is commonly used for measuring the clean water flow into apartment houses. The liquid flow rotates a turbine and a counter (or a motion sensor) counts the rotations of the turbine. The main design features are the low cost and the high reliability of the turbine-based flow-meter, but the design works well with clean liquids as, e.g., sand can damage the turbine and cause incorrect metering results.

3.1.3 Ultrasonic flow-meter

An ultrasonic flow-meter measures the velocity of the passing liquid with ultrasound. A sound impulse generated by a transducer is picked-up by an ultrasound sensor, and the frequency shift of coming waves is used to define the velocity of the flow (Figure 3).

The advantages of this design include the possibility of "non-intrusive" installation to an existing pipeline, portability, and the absence of interaction with the flow of liquid. These features make the use of the ultrasonic

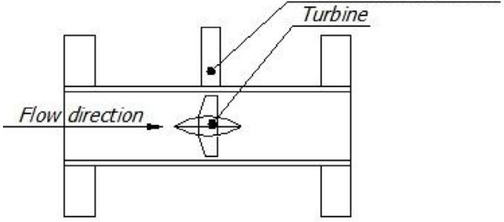


FIGURE 2
Turbine-based flow-meter

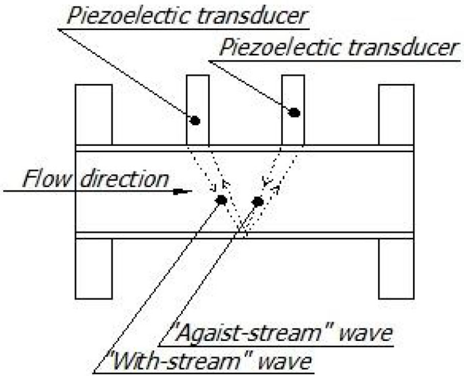


FIGURE 3
Ultrasonic flow-meter

flow-meter possible, e.g., in nuclear reactors [15]. The design is used widely, but it is relatively expensive. The characteristics of the three flow-meter designs are presented in Table 3.2.

The eight criteria observed create the basis for a multiple-criteria decision-making problem of the flow-meter selection.

3.2 Using the proposed procedure in the flow-meter design evaluation problem

Here we present by using the case numbers how the proposed procedure works in the context of the flow-meter design evaluation problem. We present a step-wise approach to using the procedure.

Step 1: Transform evaluation data into fuzzy numbers.

	EM (Piterflow RS50) [14]	**Turbine-based (Okhta T50) [16]**	**Ultrasonic (Vzloyt MR) [17]**
Cost	16150 units	4240 units	34800 units
Work time	80000 hours	100000 hours	75000 hours
Consumption	6 V*		12 V*
Accuracy (Flow-rate at specified accuracy)	36±2% m^3/hour	30,00±2% m^3/hour	35±2% m^3/hour
Operated liquids	Water, and sold water,		
Operated liquids	dirty water	Only clear water	All liquids
Ease of installation	Easy	Elementary	Average
Processing of the electronic signal	Yes	No	Yes
Shelf-time	4 years	5 years	2 years

TABLE 1
Characteristics of the three flow-meter designs

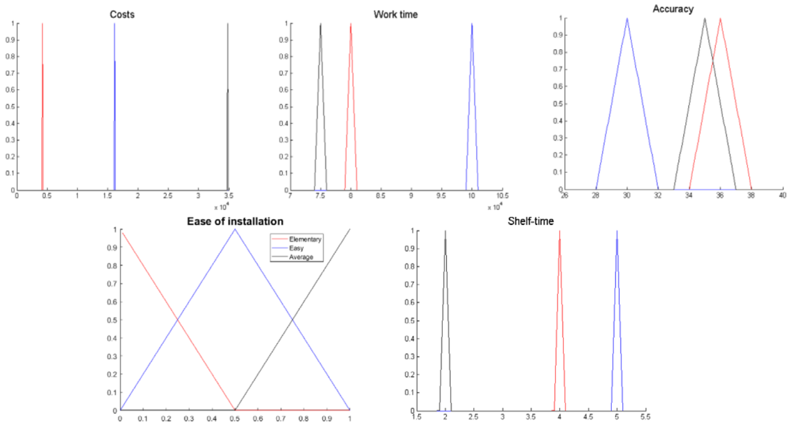


FIGURE 4
Fuzzy number representations used for five estimated criteria values

The evaluation data presented as vectors for each of the three flow-meters EM=[16150,80000,6,36,3,Easy,1,4], Turbine-based=[4242,100000,0,30,1, Elementary,0,5], and Ultrasonic=[34800,75000,12,35,20,Average,1,2] is transformed into fuzzy numbers. The fuzzy number representations of five estimated criteria values are visible in Figure 4.

Five of the nine estimated criteria values are mapped into fuzzy number representations in the following way:

Cost: Relatively small uncertainty is found in the estimation and the values are modeled by adding 5% uncertainty to both sides, meaning, e.g., that the number 34800 is modeled as a fuzzy number (33060,34800,36540). See 1 for a visual presentation.

Work time: The uncertainty is mapped by using a 1000 hour uncertainty related to the given worktime-estimates. The resulting fuzzy numbers are visible in 1.

Accuracy: For flow-meter accuracy a 2% estimation uncertainty is used. Again see 1.

Ease of installation: The linguistic values used are mapped to the unit interval that is evenly divided into three states. See 1 for details and visualization.

Shelf time: The level of uncertainty is modeled by using a “half a year uncertainty”. Again see 1

Other evaluated criteria values are assumed to be non-fuzzy. For consumption the values used are $\{0,6,12\}$, for the ability to be used with different liquids the following possible state values are used $\{1,3,20\}$, and for the processing of the electronic signal possible states are $\{0,1\}$.

	EM	**Turbine-based**	**Ultrasonic**
Cost	(0.415,0.436,0.458)	(0.109,0.115,0.120)	(0.894,0.941,0.988)
Work time	(0.718,0.727,0.736)	(0.900,0.909,0.918)	(0.673,0.682,0.691)
Consumption	(0.5,0.5,0.5)	(0,0,0)	(1,1,1)
Accuracy	(0.928,0.947,0.966)	(0.774,0.789,0.805)	(0.902,0.921,0.939)
Amount of liquid	(0.15,0.15,0.15)	(0.05,0.05,0.05)	(1,1,1)
Ease of installation	(0,0.5,1)	(0,0,0.5)	(0.5,1,1)
Signal processing	(1,1,1)	(0,0,0)	(1,1,1)
Shelf-time	(0.636,0.727,0.818)	(0.818,0.909,1)	(0.273,0.364,0.455)

TABLE 2
Normalized fuzzy evaluations for the nine criteria

Step 2: Normalization of the (fuzzy) evaluations by scaling to unit interval. The normalized values are shown in Table 2.

Step 3: Division into cost and benefit criteria and transformation into comparative unit intervals.

Five criteria are identified as benefit criteria and three as cost criteria (cost, consumption, and ease of installation). Equation (6) is applied to the cost criteria and the resulting comparable unit values are visible in Table 3.

Step 4: Interaction weight creation by using the criteria interaction matrix. The weights are created by using the procedure outlined in equations (12)-(15) to flow-meter criteria interaction matrix presented in Table 4.

The criteria interaction vector created is I=[4,1,2,1,4,2,4,0] and scaling it to the unit interval (by using $I_{max} = n = 8$) gives I =[0.5,0.125, 0.25,0.125,0.5,0.25,0.5,0]. The interaction weight vector based on the interaction vector becomes W=1-I=[0.5 0.875 0.75 0.875 0.5 0.75 0.5 1].

Step 5: We apply the FHWA-operator to aggregate the fuzzy evaluation vector and use the criteria interaction weight vector to take the information

	EM	**Turbine-based**	**Ultrasonic**
Cost	(0.541,0.564,0.585)	(0.880,0.885,0.891)	(0.012,0.059,0.106)
Work time	(0.718,0.727,0.736)	(0.900,0.909,0.918)	(0.673,0.682,0.691)
Consumption	(0.5,0.5,0.5)	(1,1,1)	(0,0,0)
Accuracy	(0.928,0.947,0.966)	(0.774,0.789,0.805)	(0.902,0.921,0.939)
Amount of liquid	(0.15,0.15,0.15)	(0.05,0.05,0.05)	(1,1,1)
Ease of installation	(0,0.5,1)	(0.5,1,1)	(0,0,0.5)
Signal processing	(1,1,1)	(0,0,0)	(1,1,1)
Shelf-time	(0.636,0.727,0.818)	(0.818,0.909,1)	(0.273,0.364,0.455)

TABLE 3
Normalized data in comparable units

	Cost	Work time	Consumption	Accuracy	Number of liquids	Ease of installation	Signal processing	Shelf- time
Cost	0	1	0	1	1	0	1	0
Work time	1	0	0	0	0	0	0	0
Consumption	0	0	0	0	1	0	1	0
Accuracy	1	0	0	0	0	0	0	0
Amount of liquid	1	0	1	0	0	1	1	0
Ease of installation	0	0	0	0	1	0	1	0
Signal processing	1	0	1	0	1	1	0	0
Shelf-time	0	0	0	0	0	0	0	0
Sum	4	1	2	1	4	2	4	0

TABLE 4
Criteria interaction matrix for the flow-meters

redundancy into consideration. The results that represent the “goodness” of the alternative flow-meter designs are (3.298, 3.799, 4.301) for the EM flow-meter, (3.873, 4.363, 4.479) for the turbine-based flow-meter, and (2.657, 2.796, 3.309) for the ultrasonic flow-meter. The results are visualized in Figure 5.

Step 6: Ranking of the alternatives based on the fuzzy results. The ranking is done by using the method by Kaufmann and Gupta presented above and the ordering from the first to the third best respectively is turbine-based, EM and ultrasonic flow-meter.

It can be observed that the ranking step is quite unnecessary in this simple example however with a larger number of alternatives the final ranking of alternatives becomes more important.

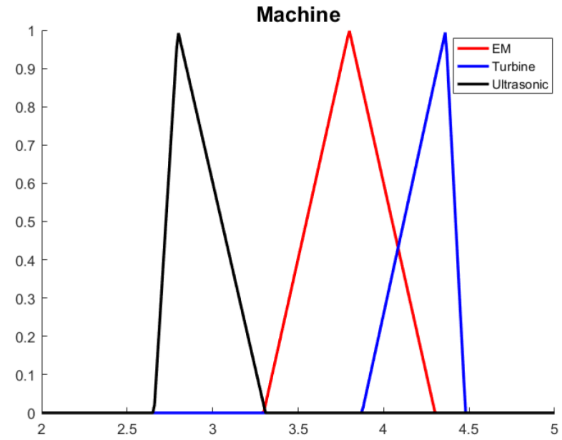


FIGURE 5
Final results for the three flow-meter designs

4 CONCLUSIONS

This paper has proposed a new multiple-criteria decision-making procedure for design evaluation that in contrast to existing techniques is able to consider the interdependency between the criteria of evaluation. The proposed method is based on using normative expert estimates for the evaluation and uses fuzzy number representations of the estimated criteria values in order to account for the evaluation imprecision.

By using a an evaluation matrix for the interaction of the considered criteria we are able to create a vector of weights that represent the redundancy of information in each criterion in a manner ‘the higher the information contained within a criterion is the same with the information contained within other criteria, the lower the information weight of the criterion’. In this way the proposed method removes the biasing effect of information redundancy from the evaluation. The fuzzy heavy weighted averaging operator that allows the inclusion of the information weights in the aggregation of multiple criteria is used in the generation of the final goodness-values for the evaluated design alternatives. These resulting fuzzy numbers are then ordered to find the final ranking of the evaluated designs. The use of the proposed procedure is demonstrated with a simple case of flow-meter design selection problem.

Even if the proposed procedure is here presented in connection with design evaluation the principles presented are generic and can be applied to a great variety of decision problems that involve the comparison of alternatives with multiple-criteria that exhibit information redundancy. Future research in vein with the presented procedure can concentrate on taking the use of the interaction matrix further in terms of creating more advanced procedures for eliciting and handling estimates about interaction between criteria, including also research into aggregating multiple expert estimates of criteria interaction.

REFERENCES

[1] Ullman, D.: The mechanical design process 4th edition. McGraw-Hill (2010).

[2] Okudan, G.E., Tauhid, S.: Concept selection methods - a literature review from 1980 to 2008. *Int. J. Des. Eng.*, 1, 243–277 (2008).

[3] Saaty, T.: The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill (1980).

[4] Pugh, S.: Creating innovative products: using total design: the living legacy of Stuart Pugh. Addison-Wesley Publishers (1996).

[5] Yoji, A.: Development History of Quality Function Deployment. The Customer Driven Approach to Quality Planning and Deployment. Asian Productivity Organization, Tokyo (1994).

[6] Efimov-Soini, N., Kozlova, M., Collan, M., Luukka, P.: A multi-criteria decision-making tool with information redundancy treatment for design evaluation. *In: Proceedings of the NSAIS'16 Workshop on Adaptive and Intelligent Systems*, 2016. pp. 73–75. , Lappeenranta, Finland (2016).

[7] Collan, M., Luukka, P: Strategic R&D project Analysis: Keeping it simple and smart. Using fuzzy scorecards to collect data for strategic R&D projects & analyzing and seleting projects with a system that uses new fuzzy weighted averaging operators, Studies in Fuzziness and Soft Computing, 335, 169–191, (2016).

[8] Kaufmann, A., Gupta, M.: Introduction to fuzzy arithmetic: Theory and applications. Van Nostrand Reinhold Co, (1985).

[9] Mansor, M.R., Sapuan, S.M., Zainudin, E.S., Nuraini, A.A., Hambali, A.: Conceptual design of kenaf fiber polymer composite automotive parking brake lever using integrated TRIZ-Morphological Chart-Analytic Hierarchy Process method. *Mater. Des.*, (2014).

[10] Di Gironimo, G., Carfora, D., Esposito, G., Labate, C., Mozzillo, R., Renno, F., Lanzotti, A., Siuko, M.: Improving concept design of divertor support system for FAST tokamak using TRIZ theory and AHP approach. *Fusion Eng. Des.*, (2013).

[11] Codina Gironès, V., Moret, S., Maréchal, F., Favrat, D.: Strategic energy planning for large-scale energy systems: A modelling framework to aid decision-making. Energy. 90, 173–186 (2015).

[12] Matzen, M., Alhajji, M., Demirel, Y.: Chemical storage of wind energy by renewable methanol production: Feasibility analysis using a multi-criteria decision matrix. Energy. 93, 343–353 (2015).

[13] Thakker, A., Jarvis, J., Buggy, M., Sahed, A.: 3DCAD conceptual design of the next-generation impulse turbine using the Pugh decision-matrix. (2009).

[14] Electromagnetic flow meters "Peterflow," http://termotronic.ru/products/piterflow/.

[15] Katronic overwiew, http://katronic.com/industries/overview/?no_cache=1&sword_list%5B%5D=nuclear.

[16] Turbine flowmeter Okhta, http://termotronic.ru/products/ohta-t.

[17] Ultrasonic flow meter Vzloit MR, http://vzljot.ru/catalogue/ultrazvukovoj_metod/vzlet_mr_ursv-1hh_c/.

[18] Carlsson, C., Fullér, R.: Multiple criteria decision making: The case for interdependence, Computers & Operations Research, 22, 3, 251–260, (1995).

[19] Carlsson, C., Fullér, R.: Interdepence in multiple criteria decision making, in Multicriteria analysis, Proceedings of the XIth international conference on MCDM, 25–36, (1997).

[20] Carlsson, C., Fullér, R.: Interdependence in fuzzy multiple objective programming, *Fuzzy Sets and Systems*, 65, 19–29, (1994).

[21] Yager, R.R.: Heavy OWA operator, *Fuzzy optimization and decision making*, 1,4, 379–397, (2002).

[22] Zadeh, L.A.: Fuzzy sets, *Information and Control*, 8,1, 338–353, (1965).

[23] Bellman, R.E., Zadeh, L.A.: Decision-making in a fuzzy environment, *Management Science*, 17,4, 141–164, (1970).

[24] Carlsson, C., Fullér, R.: Fuzzy multiple criteria decision making: Recent developments, *Fuzzy sets and systems*, 78, 139–153, (1996).

[25] Ribeiro, R.A.: Fuzzy multiple attribute decision making: A Review and New Preference Elicitation Techniques, *Fuzzy sets and systems*, 78, 155–181, (1996).

[26] Kahraman, C., Onar, S.C., Oztaysi, B.:Fuzzy Multicriteria decision-making: a literature review, *International journal of computational intelligence systems*, 8,4, 637–666, (2015).

[27] Roy, B.: Classement et choix en présence de points de vue multiples (la méthode ELECTRE), RIBO, 8, 57–75, (1968).

[28] Brans, J.T., Vincke, Ph.: A preference ranking organisation method:(The PROMETHEE method for multiple criteria decision-making), *Management Science*, 31,6, 647–656, (1985).

[29] Kilgour, D.M., Eden, C.: Handbook of group decision and negotiation, Advances in group decision and negotiation, 4, (2010).

[30] Zeleny, M.: Multiple criteria decision making, McGraw-Hill, (1982).

[31] Keeney R, Raiffa H,: Decisions with Multiple Objectives, Preferences, and Value Tradeoffs. John Wiley, Hoboken, NJ (1976).

ACTA UNIVERSITATIS LAPPEENRANTAENSIS

804. TIAINEN, JONNA. Losses in low-Reynolds-number centrifugal compressors. 2018. Diss.

805. GYASI, EMMANUEL AFRANE. On adaptive intelligent welding: Technique feasibility in weld quality assurance for advanced steels. 2018. Diss.

806. PROSKURINA, SVETLANA. International trade in biomass for energy production: The local and global context. 2018. Diss.

807. DABIRI, MOHAMMAD. The low-cycle fatigue of S960 MC direct-quenched high-strength steel. 2018. Diss.

808. KOSKELA, VIRPI. Tapping experiences of presence to connect people and organizational creativity. 2018. Diss.

809. HERALA, ANTTI. Benefits from Open Data: barriers to supply and demand of Open Data in private organizations. 2018. Diss.

810. KÄYHKÖ, JORMA. Erityisen tuen toimintaprosessien nykytila ja kehittäminen suomalaisessa oppisopimuskoulutuksessa. 2018. Diss.

811. HAJIKHANI, ARASH. Understanding and leveraging the social network services in innovation ecosystems. 2018. Diss.

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. YLA-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 paraller-connected grid inverters. 2018. Diss.

827. RANAEI, 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.

LUT University

ISBN 978-952-335-340-4
ISBN 978-952-335-341-1 (PDF)
ISSN-L 1456-4491
ISSN 1456-4491
Lappeenranta 2019