UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

GENERATIVE DESIGN METHODS AND ALGORITHMS FOR COMPONENTS PRODUCED BY DIFFERENT MANUFACTURING TECHNOLOGIES

Theses of the PhD thesis

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1. INTRODUCTION

From everyday products to components used in special tools, machines and various production equipment, it can be said that continuous development and innovation are considered to be a constant goal.

Market and social demands, as well as the development of technical sciences, continuously force these products and components to be reborn every day with a new appearance or possibly by meeting new functional criteria. The continuous development, design and simulation verification of these products or components requires a large financial outlay, coupled with an enormous amount of engineering, intellectual and physical work. These invested resources aim to keep up with consumer demands and the rapid development of industry. Apart from this, the factual statement and approach that evaluates design activities based on economic considerations is still valid, namely that the expected costs of resolving design errors discovered early in the design process are the lowest, considering the entire life cycle of a product. Based on this logic, the design engineer has the greatest responsibility throughout the entire design and development process. Accordingly, we consider it as a true statement that the greatest economic result with the least effort could be achieved through technical development. With the help of computer technology, the generative design model was created, which reforms the methods, approaches, and various rule systems of classical design methodologies. The design model imitates the nature's evolutionary approach to provide thousands of solutions to a single engineering problem. Using software based on artificial intelligence and leveraging the power of computers, it allows engineers to create hundreds or even thousands of design variants by defining a design problem, i.e. by specifying basic parameters such as geometric dimensions, loads, strength, and material variants. By combining this type of design method with the positive properties provided by additive manufacturing technology, objects or special components can be created in a relatively short time that are more material-efficient, thus lighter or, in some cases, more load-bearing, i.e. stronger, than components produced by traditional processes.

The aim of my research is to examine the currently applied design methodology principles for the generative design method and their applicability in generative design processes, as well as to develop a new design methodology approach for generative design, taking into account the production of the product by using additive manufacturing technology.

2. OBJECTIVES OF THE DISSERTATION

The productivity characteristics of modern, currently developed manufacturing equipment show continuous improvement, without any deterioration in accuracy parameters. This phenomenon is mainly due to the control of automated manufacturing equipment, which has undergone rapid development in recent decades. The expected properties and quality parameters of a manufactured product, component or other invention are greatly influenced by the applied design method and the capabilities and nature of the production equipment used for production. Therefore, development and continuous innovation are important so that the accuracy, mechanical and dynamic properties of machines improve, which serve both the development trends of new machine tools and the quality expectations for the products produced on those machines. The mechanical design school of Miskolc uses the concept of the so-called mother machine, since all parts, machine elements and machines are produced on machine tools, therefore it is particularly important to increase the accuracy and reliability of machine tools, their main units, sub-assemblies and their components. The machining accuracy and productivity of a machine tool can be influenced by several factors, such as mechanical and dynamic rigidity or positioning accuracy and repeatability. A significant technical progress can be observed in the last decades in the field of manufacturing technology, as additive machining has developed and became increasingly widespread, which has a continuous motivating force in the development of additive machine tools. These innovative processes force related disciplines, such as the methodology and approach of machine and product design, to keep up with modern expectations. My research focuses mainly on new design methodologies and my main goal is to use the research to determine how products and components created through a generative design process assisted by artificial intelligence with the power of novelty are integrated into the approaches and tools of classical machine design. Further objectives include examining the design methodology principles currently applied to the generative design process and their applicability in generative design processes, as well as developing a new design methodology approach and design method for generative design, taking into account the construction of the product using additive manufacturing technology. In the dissertation, I conduct a detailed literature review and then analyze the scientific field of traditional design methodology principles and their applicability in the generative design process. I examine the role of generative design processes in the design and production of machine tool components, which I present with a case study. Finally, I propose a new design methodology description for the generative design process.

3. DETAILED DESCRIPTION OF THE COMPLETED TASKS

The aim of the dissertation is to investigate generative design methods, which seeks to answer the question of which design approach and in which design steps it is appropriate to solve a given task. During my research, I studied the historical background, based on which literature overview was formulated as regards for the development of design methodology and topology optimization. I examined the main design approaches, into which I included generative design and its principles. Focusing on the design of technical products, I examined the logical steps and tasks of serial, parallel, and generative design processes, which was summarized with a comparison. I conducted research on the topic of computer-aided generative design, during which I reviewed the theoretical foundations of topology optimization, and the different types of it, which is the basis of the procedure. I summarized the process of development and integration of generative software and studied the structure of the generative design modules of the most common iCAD systems and the steps required for the usage which is characterized with a flowchart. I examined the role of generative design in the science of machine tool design using a case study on the development of an automatic tool changer mechanism. During the study, I applied a new methodological description. and formulated new evaluation criteria for the solutions created, during which I produced the optimal solution.

In the course of the dissertation, I proposed a methodological description that complements the classical methodological descriptions. Generative design is referred to in the profession as a “paradigm shift”, which should be sought primarily in the description method, i.e. in the coding of possible solutions. The proposed method and approach can provide support in the systematic description, differentiation, characterization and evaluation of constructions and products built from the permutation of amorphous and regular geometries.

The opportunity for further development could be the integration of new description and evaluation features for constructions and solutions into various topological optimization and generative design modules. Embedding in software could help in the systematic structure of simulation models based on coding and their objective evaluation. The precise definition of manufacturability features that influence the value of relative safety and real safety improves the estimation of the properties of the expected results.

4. NEW SCIENTIFIC RESULTS

T1. I developed a new description method for constructs generated by a generative design process and introduced the construction space relationship matrix **X**, which divides the design space into a base set, subsets, and a real subset. In the matrix **X**, the arguments of each set are defined by binary encoding of the functions.

$$\mathbf{X} = \begin{array}{c} \\ H \\ A \\ B \\ C \\ D \end{array} \begin{array}{c} \begin{array}{ccccc} F_1 & F_2 & F_3 & F_i & F_n \end{array} \\ \begin{bmatrix} 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 1 \\ 1 & 0 & 0 & \dots & 0 \\ 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \end{bmatrix} \end{array}$$

- The first row of the **X** construction space relationship matrix is always the base set, which represents the entire design volume for the component. The subsequent rows contain the individual subsets, which represent the individual construction geometries. The functions of the component are located on the columns of the matrix. Each matrix element can take a binary value, which is 1 if the given subset contains the function, otherwise it is 0.
- The designer can freely define the bound geometries. In many cases, this creative freedom can be aimed at satisfying aesthetics functions. The subsets describing the relationship of functions do not prioritize the individual relationships, only their existence is important. The logical relationships in the graph, equation and structure matrix descriptions of functions do not limit the establishment of subsets, they can only provide help in determining what segmentation and grouping should be created by the individual construction geometries. In case when the shape features attached to two functions are closely related to each other, or are located on top of each other, separation is not justified.
- By highlighting individual rows of the **X** matrix, the function connection vector for the construction geometries can be created.

T2. For constructions created by generative design process, I introduced the generated relationship matrix **G**, which describes the material relationship generated by the software between the functions of the produced solutions and the construction volumes.

$$\mathbf{G} = \begin{array}{c} \\ H \\ A \\ B \\ C \\ D \end{array} \begin{array}{c} \begin{array}{ccccc} F_1 & F_2 & F_3 & F_i & F_n \end{array} \\ \begin{bmatrix} 0 & 0 & 0 & \dots & 0 \\ x & 0 & x & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & x \\ x & 0 & 0 & \dots & 0 \end{bmatrix} \end{array}$$

- The first row of the generated connection matrix **G** always contains the base set, which embodies the entire design volume for the component. The subsequent rows contain the individual subsets, which form individual construction geometries. The functions of the component are located on the columns of the matrix. Each matrix element can take a binary value, which is *x* if the given subset has received the connection generated by the software with the given function, otherwise it represents the value 0.

T3. For constructions generated by generative design methods, I introduced the solution matrix M, which I derived using the relation $\mathbf{X} + \mathbf{G} = \mathbf{M}$. The **M** matrix describes the relationship between the functions and construction geometries of the generated solutions by distinguishing predefined and software-generated material relationships.

$$\mathbf{M} = \begin{matrix} & F_1 & F_2 & F_3 & F_i & F_n \\ H & 0 & 0 & 0 & \dots & 0 \\ A & 0 & 0 & 0 & \dots & 1 \\ B & 1 & 0 & 0 & \dots & 0 \\ C & 0 & 1 & 0 & \dots & 0 \\ D & 0 & 0 & 1 & \dots & 0 \end{matrix} + \begin{matrix} & F_1 & F_2 & F_3 & F_i & F_n \\ H & 0 & 0 & 0 & \dots & 0 \\ A & x & 0 & x & \dots & 0 \\ B & 0 & 0 & 0 & \dots & 0 \\ C & 0 & 0 & 0 & \dots & x \\ D & x & 0 & 0 & \dots & 0 \end{matrix} = \begin{matrix} & F_1 & F_2 & F_3 & F_i & F_n \\ H & 0 & 0 & 0 & \dots & 0 \\ A & x & 0 & x & \dots & 1 \\ B & 1 & 0 & 0 & \dots & 0 \\ C & 0 & 1 & 0 & \dots & x \\ D & x & 0 & 1 & \dots & 0 \end{matrix}$$

- The elements of the matrix **M** can take the characters 0, 1 and *x*. If a matrix element has the value 1, the given subset contains the function and the relationship is considered a predefined boundary condition, otherwise it represents the value 0. If a matrix element contains the character *x*, then it is a software-generated function and construction space relationship.

T4. I introduced the generated function structure matrix $\mathbf{F}_g$ for constructions produced by generative design processes. The $\mathbf{F}_g$ matrix complements the description method common in the field of methodical design by differentiating predefined and software-generated material relationships in case of function relationships. The **M** matrix helps in creating the $\mathbf{F}_g$ matrix.

$$\mathbf{F}_g = \begin{matrix} & F_1 & F_2 & F_3 & F_i & F_n \\ F_1 & 0 & 1 & x & \dots & 1 \\ F_2 & x & 0 & 1 & \dots & x \\ F_3 & 1 & x & 0 & \dots & 1 \\ F_j & \dots & \dots & \dots & 0 & \dots \\ F_n & x & 1 & x & \dots & 0 \end{matrix}$$

- The main diagonal of the generated function structure matrix $\mathbf{F}_g$ contains 0 elements. The columns and rows of the matrix are formed by the functions that build the generated part. Each matrix element can take the values 0, 1 and *x*. If the value is 1, then there is a predefined material relationship between the functions belonging to the given row and column. If a matrix element represents a value of *x*, then a software-generated material connection has been established between the function pair belonging to the given row and column. In the case of a value of 0, there is no direct material connection between the function pair.

T5. I developed indicators derived from geometric and physical properties as an evaluation system for products and components produced by the generative design process. I introduced the concepts of the generation constraint $g_{(k)}$ the generation freedom $g_{(sz)}$ and the degree of generality γ_i, which can be determined from the geometric feature. I introduced the relative safety factor $b_{i(r)}$ and the real safety factor $b_{i(v)}$ which can be calculated based on the physical properties.

$$g_{(k)} = \left[\frac{V_{i(k)}}{V_o}\right] \cdot 100, \quad g_{(sz)} = \left[1 - \frac{V_{i(k)}}{V_o}\right] \cdot 100 \quad \text{és} \quad \gamma_i = \left[\frac{V_{i(ga)}}{V_{i(k)}}\right] \cdot 100$$

– The volume bounded by the construction spaces $V_{i(k)}$ in percentage form compared to the initial design volume V_0 is given by $g_{(k)}$. The generation freedom $g_{(sz)}$ is the inverse of $g_{(k)}$, which gives the design volume V_0 that can be freely generated by the software as a function of the volume bounded by the construction spaces $V_{i(k)}$. From the geometry described based on the matrix **X,** $g_{(k)}$ and $g_{(sz)}$ can be derived. The two parameters are important indicators of a topology optimized part, as they serve as a fundamental basis for comparison in the design and evaluation stages.
– The degree of generality γ_i shows the proportion of the material volume generated by the software compared to the bound construction volumes. The result is given as the volume ratio of the generated material $V_{i(ga)}$ to the construction spaces $V_{i(k)}$ in percentage form. γ_i can be derived from the geometry described based on the matrix **M**.

$$b_{i(r)} = \frac{\sigma_{meg}}{\sigma_{i(max)}} \geq 1 \quad \text{és} \quad b_{i(v)} = \frac{R_{p0,2}}{\sigma_{i(max)}}, \quad \text{ahol:} \quad \sigma_{meg} = \frac{R_{p0,2}}{b}$$

– The relative safety factor shows the difference between the allowable stress value σ_{meg} given before generation and the maximum stress $\sigma_{i(max)}$ that develops in the i^{th} generated construction. The difference between the two stress values shows how much reserve there is in the system from a static point of view. The difference is actually the result of the constraints and limitations on the geometry, which are determined by the manufacturability rules assigned to the chosen production technology. The real safety factor $b_{i(v)}$ for the i^{th} construction can be interpreted in relation to the yield strength of the material. These two indicators can be appropriate evaluation criteria in the evaluation phase of systematic design, with the help of which the individual solutions can be classified objectively (27).

5. LIST OF PUBLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

Conference presentations in Hungarian language

(1) Szabó, K.: *A genetikai algoritmusok alapjai*, A PEME XXV. PhD – Konferenciájának előadásai, poszterszekció, Budapest, Magyarország: Professzorok az Európai Magyarországért Egyesület (2023. április 27. Budapest)

(2) Szabó, K.: *A genetikai algoritmusok működésének áttekintése*, XXVI. Tavaszi Szél Konferencia 2023, poszterszekció, Miskolc, Magyarország: Doktoranduszok Országos Szövetsége (2023. május 5., Miskolc, Miskolci Egyetem A4 főépület)

(3) Szabó, K.: *Component Development by Simulation-Driven Design Method*, InnoVeTAS, (2025. május 9., online prezentéció)

Foreign language conference presentations

(4) Szabó K.: *Design of Chip Conweyor*, 7th International Scientific Conference on Advances in Mechanical Engineering (ISCAME 2019), Debrecen, Hungary: Department of Mechanical Engineering, Faculty of Engineering, University of Debrecen 07-08th November (2019)

(5) Szabó, K.: *Investigation of the Applicability of Topological Methods*, Lecture Notes in Mechanical Engineering (2195-4356 2195-4364): Vehicle and Automotive Engineering 4 pp 582-591 Paper Chapter 49. (2022) 4th International Conference on Vehicle and Automotive Engineering, Conference place and date: Miskolc-Egyetemváros, Magyarország 2022.09.08. - 2022.09.09.

(6) Szabó, K.: *Component development using Topological Methods*, 8th International Scientific Conference on Advances in Mechanical Engineering (ISCAME 2022), Debrecen, Hungary: Department of Mechanical Engineering, Faculty of Engineering, University of Debrecen 10-11th November (2022)

(7) Szabó, K.: *Application of Topological Methods in the development of Vehicle components*, 8th International Scientific Conference on Advances in Mechanical Engineering (ISCAME 2022), Debrecen, Hungary: Department of Mechanical Engineering, Faculty of Engineering, University of Debrecen 10-11th November (2022)

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(8) Szabó, K.: *A genetikai algoritmusok alapjai*, A PEME XXV. PhD – Konferenciájának előadásai, Budapest, Magyarország: Professzorok az Európai Magyarországért Egyesület, pp. 218-226. (2023)

Hungarian language articles in journals

(9) Szabó, K.: *Forgácskihordó rendszerek tervezésmódszertanának vizsgálata*, Multidisciplinary Sciences, University of Miskolc, 9: 4 pp. 517-522., 6 p. (2020)

(10) Szabó, K., Hegedűs, Gy.: *A generatív tervezést támogató szoftverek rövid áttekintése*, Multidiszciplináris Tudományok: A Miskolci Egyetem közleménye 10: 3 pp. 328-337., 10 p. (2020)

(11) Szabó, K., Hegedűs, Gy.: *A generatív tervezés lépései integrált CAD rendszerekben*, Multidiszciplináris Tudományok: A Miskolci Egyetem közleménye 10: 4 pp. 393-398., 6 p. (2020)

(12) Szabó, K.: *Topológiai módszerek alkalmazása*, Multidiszciplináris Tudományok: A Miskolci Egyetem közleménye 11: 4 pp. 218-226., 9 p. (2021)

(13) Szabó, K.: *Tervezésmódszertani esetvizsgálatok*, Multidiszciplináris Tudományok: A Miskolci Egyetem közleménye 11: 2 pp. 123-128., 6 p. (2021)

(14) Szabó, K.: *Topológiai módszerek alkalmazása járműalkatrészek fejlesztésében*, Kutatási eredmények a Miskolci Egyetem Gépészmérnöki és Informatikai Karának Szerszámgépészeti és Mechatronikai Intézetében – 2022, Miskolc-Egyetemváros: Miskolci Egyetem, Gépészmérnöki és Informatikai Kar, Szerszámgépészeti és Mechatronikai Intézet, pp. 109-117. (2022)

(15) Szabó, K.: *A genetikai algoritmusok rövid áttekintése*, Kutatási eredmények a Miskolci Egyetem Gépészmérnöki és Informatikai Karának Szerszámgépészeti és Mechatronikai Intézetében – 2022, Miskolc-Egyetemváros: Miskolci Egyetem, Gépészmérnöki és Informatikai Kar, Szerszámgépészeti és Mechatronikai Intézet, pp. 101-108. (2022)

(16) Szabó, K.: *A genetikai algoritmusok működésének alapjai*, Kutatási eredmények a Miskolci Egyetem Gépészmérnöki és Informatikai Karának Szerszámgépészeti és Mechatronikai Intézetében – 2022, Miskolc-Egyetemváros: Miskolci Egyetem, Gépészmérnöki és Informatikai Kar, Szerszámgépészeti és Mechatronikai Intézet, pp. 101-108. (2022)

(17) Szabó K.: *A számítógép segítette tervezési módszerek hatása a műszaki tervezésben*, GÉP (0016-8572 3057-9473): 75 3-4 pp. 109-112. (2024)

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(18) Szabó, K.: *Design of Chip Conveyor*, Internal Journal of Engineering and Management Sciences / Műszaki és Menedzsment Tudományi Közlemények 5: 2 pp. 81-85. (2020)

(19) Szabó K., Hegedűs, Gy.: *Brief Overview of Generative Design Support Software*, Design of Machines and Structures Vol. 10: No. 2 pp. 123-132. (2020)

(20) Szabó, K.: *Application of Topological Methods*, Design of Machines and Structures Vol. 11, No. 1, pp. 59-68. (2021)

(21) Szabó, K.: *Steps of Generative Design in Integrated CAD Systems*, Design of Machines and Structures Vol. 11, No. 1, pp. 53-58. (2021)

(22) Szabó, K.: *Investigation of the Applicability of Topological Methods*, Lectura Notes in Mechanical Engineering (2195-4356 2195-4364): Vehicle and Automotive Engineering 4 pp. 582-591 Paper Chapter 49. (2022) 4th International Conference on Vehicle and Automotive Engineering

(23) Szabó, K.: *Component development using Topological Methods*, Internal Journal of Engineering and Management Sciences / Műszaki és Menedzsment Tudományi Közlemények, (IJEMS) Vol. 8. No. 2. pp. 54–62. (2023)

(24) Szabó, K.: *Application of Topological Methods in the development of Vehicle components*, Internal Journal of Engineering and Management Sciences / Műszaki és Menedzsment Tudományi Közlemények, (IJEMS) Vol. 8. (2023). No. 1. pp. 67–75. (2023)

(25) Szabó, K.: *A Brief Overview of Genetic Algorithms*, Design of Machines and Structures (1785-6892 2064-7522): Vol. 13 No. 2, pp. 113-120. (2023)

(26) Szabó, K.: *The impact of computer tools systems on design methodology processes and approaches*, Multidiszciplináris Tudományok: A Miskolci Egyetem közleménye (2062-9737 2786-1465): 14(3) pp. 25-34. (2024)

(27) Szabó, K.: *Component Development by Simulation-Driven Design Method*, InnoVeTAS, (2025) (under review)