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Automation of the conceptual design in engineering project management based on morphological approach

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ABSTRACT

The article discusses the formalization and automation of the search for new engineering and technological solutions. Attention is drawn to some issues associated with approaches relying purely on human estimations and experience for the purpose of solving structural problems. In order to reduce these, the prospect of software tool introduction for the automation of the conceptual design process is presented. Particularly, global requirements for Computer-Aided Innovation tools are outlined and positioned within the classification of such software. The main challenges include the creation of approaches that allow early processing of information flows and produce some set of possible solutions. The focus lies in improving the efficiency of design studies and reducing the time spent on the entire process creation cycle. The Advanced Morphological Approach is presented as a successful example of addressing some of the mentioned challenges. The future implementation of the proposed software would allow to create a space of feasible design problem solutions, ideally resistant to changes of the external environment.

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1. Introduction

One of the important challenges in the search for new technological solutions remains the necessity for further conceptual design process formalization. The methods for defining and solving structural analysis and synthesis problems are divided into two main classes: transformational and morphological. The transformational approach relies on the extensive use of human creativity. However, in the process of synthesis, unexpected circumstances may arise due to some characteristic features of human reasoning. The fact is that the researcher has a certain predilection for given ordinary approaches, which are comprehensible to them. At the same time, original ways of solving are not usually referred to as "regular" methods. Regularity manifests itself either in giving the structures visually "correct" features - symmetry, hierarchy, repetition and periodicity, or in deriving the structure itself from a certain analogy. Ultimately, this can lead to the development of a pattern, which itself can affect the quality of the results of structural synthesis. Many researchers draw attention to some of the dangers in using purely human approaches for the solution of structural problems.

The initial form or the overall structure of the object to be designed has an impact on its final form. The peculiarity of human decision-making is such that once the initial structure appears, it is most likely to be followed as a model for further development. Full automation of transformational methods is fundamentally impossible. All morphological methods are based on a combinatorial approach. The Morphological Analysis

(MA) procedure allows to purposefully and systematically lay down a huge number of analogues in morphological sets of engineering solutions. Some stages of morphological methods can be automated. The general conclusion from the above analysis is that automated design should cover not only the final stages, but also the search for initial product concepts. Without modern computer technology it is practically impossible to examine and evaluate a large number of possible solutions and technical innovations.

Thus, the MA has been used in dozens of developments in project management. The morphological box for education for sustainable development (ESD) provides more than 70 million opportunities to systems implement. Universities may use this morphological box for ESD to find out their unique profile and develop proper ways to implement ESD (Isenmann et al., 2020).

The analysis has been used to complex selection process of worker assistance systems for human-centered manufacturing systems. Due to rising complexity of products and processes in the manufacturing sector, as well as changing work environments, the choice for suitable support systems on the shop floor becomes more difficult. In this work the researchers identify a broad variety of influencing attributes for selecting the most appropriate worker assistance systems depending on each individual field of application. These attributes are building the ground for the development of a morphological box to facilitate the selection process of worker assistance systems (Späker et al., 2021).

The study analyzed new electricity business cases with an aim to categorize them systematically based on theoretical grounds. Complementing the shortcomings, researchers adopted the morphological box for categorization to compare several business cases and draw the main types of businesses. It has revealed that utilities as well as residential, commercial, industrial customers also act as the main customers for the distributed resources while cooperation among different industries is growing rapidly, and local governments are actively involved in the business as the main providers (Park & Lee, 2020).

The MA results indicate that the present state of developing and maintaining B2C systems has not been much influenced by modern Web Engineering concepts and that there is considerable potential for improvement (Knolmayer & Borean, 2010).

The investigates proposes a planning methodology of systems technologies using a three-dimensional morphological box. The authors assume that the planning problem of systems technologies could be represented by three basic attributes, i.e., needs (system requirements), seeds (basic technologies) and systems technologies (system problems). They introduce a three-dimensional morphological box, whose axes are the above attributes, as a framework of planning activities. The constituent items of each axis are obtained from the recognition of societal and technological trends (Nakao, 2001).

In the work the concept of human-machine collaboration is regarded as key enabler for agile production systems as collaborative robots offer new forms of flexibility. Due to inherent safety functionalities, these robots can operate without physically separating safety devices and thus provide flexibility in task allocation and execution. The paper presents the impact of modifications on collaborative robotic cells and how they influence the risk assessment. Furthermore, a method of considering work system variants based on desired future modifications is presented so that implications can be already identified in an early design phase of the system (Komenda et al., 2021).

This research builds upon the methodological literature on developing and evaluating energy scenarios and presents a morphological box, which comprises parameters describing the scenario properties, (energy system) model properties, scientific practice and institutional settings of energy scenarios. The newly developed morphological box is applied to four selected energy scenarios of the energy transition (Witt et al., 2018). Morphological approaches have also been used in a number of other works (Zwicky,1969), (Levin, 2015).

Among the tasks encountered during the design of engineering and technological processes, one can highlight the following (Rakov, 2010):

a) Creation of approaches that allow in the early stages of process creation to process information flows and produce some set of possible solutions;
b) Increasing the efficiency of design research and reducing the time spent on the whole cycle of process creation;
c) Increasing the number of options under consideration, determining the optimal modes of operation and taking into account the influence of the external environment;
d) Use of new methodological approaches to problem solving;
e) Increasing the effectiveness of design research;
f) Satisfying the conditions of competitiveness, high quality requirements, manufacturing feasibility, etc;
g) Selection of the best process structure, implementation of the optimal organization of the elements interaction, determination of the optimal functioning modes and consideration of the external environment impact;
h) Automation of prospecting works.

2. Conceptual Design

The initial stage of product development is denoted as conceptual design (Gost, 2013). Typically, it encompasses the following tasks:

a) The implementation of options for possible solutions, the establishment of the peculiarities of options. The depth of such study should be sufficient to compare the options under consideration;
b) Development and justification of engineering solutions aimed at ensuring the indicators established by the terms of reference and the technical proposal;
c) Assessment of the product’s manufacturing feasibility and ensuring the correct choice for means and methods of control (testing, analysis, measurement);
d) Evaluation of the product in terms of its compliance with the requirements of ergonomics and technical aesthetics;
e) Check of variants for patent purity and competitiveness;
f) Comparative assessment of the options under consideration. The comparison is carried out according to product quality indicators (purpose, reliability, manufacturing feasibility, standardization and unification, economic, aesthetic, ergonomic).
g) Choosing the best (rational) option(s) for the product and justifying the choice;
h) Decision-making tasks;
i) Confirmation or clarification of the product requirements (engineering characteristics, quality indicators, etc.) and definition of technical and economic characteristics.

The significant information uncertainty encountered during conceptual design leads to the consideration of “crude” models and multi-variant design solutions, i.e. parallel processing of a number of alternative variants. Such a detailed system and mathematical study needs to reproduce the interaction of external and internal factors during the design process. The automation of the process itself creates patterns in the solution space influenced by the defining process characteristics. The development of project cost, cost influence and uncertainty of information over project lifetime is shown in Figure 1 (Bardenhagen, 2019; Rakov, 2020).

Various methods have been developed for conceptual design. These methods include genetic algorithm (Boutemedjet et al., 2019), matrix-based methods (Geng et al., 2011), exergy methods (Zhy et al., 2018), axiomatic design (Thielman & Ge, 2006) etc. At present, there exist many methods to search for and synthesize engineering solutions, including processing Big Data in Internet (Hashimova, 2016) and structural analysis for the realization of scientific and engineering ideas (Aliyev & Shahverdiyeva, 2017).

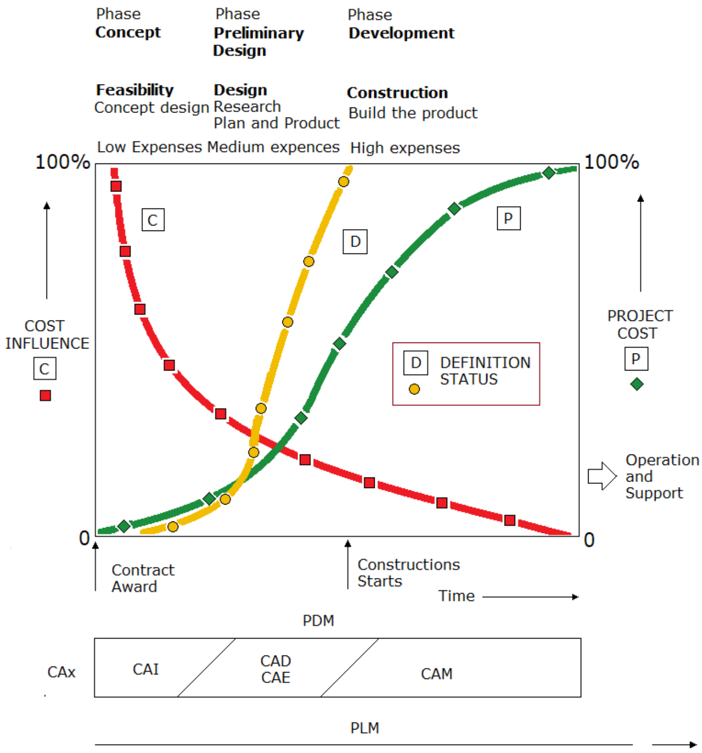


Figure 1. Change in project cost, cost influence and uncertainty of information

The design of a product, system or process can be summarized by the definition of the product structure (structural synthesis) and of the parameter range for the synthesized structure (parametric synthesis or parametric optimization). The completely different character of these tasks implies different solution strategies. Parametric synthesis could be usually resolved by reducing the task to the determination of solutions satisfying the metric criteria. On the contrary, structural synthesis defines the rational structure of an object and is generally classified as formally non-resolvable. Such tasks involve working with uncertain structural connections, non-metrical attributes of structural elements and quality criteria. Conventional optimization methods cannot be applied to a certain objective function of structural synthesis due to its following qualities: (1) it is discontinuous (discrete) or cannot always be determined; (2) it exists in operator notation; (3) it is not based on analytical expressions; (4) it is not differentiable, not unimodal, not separable, and not additive (Mishin & Osin, 1978; Rakov 2019,2020). The solution of the structural synthesis task is the main and exclusive subject of the researcher's creative activity.

During the stage of structural synthesis of new engineering solutions intuitive (Brainstorming, Mind Mapping, TRIZ, Synectics etc.) and discursive (morphological analysis, cause-and-effect diagram, Osborn-Checklists etc.) techniques can be used.

3. Automation of the conceptual design stage

The most intuitive techniques for idea generation such as brainstorming and mind mapping rely mostly on subjective human judgment, experience and decision-making. Although for the design of complex engineering solutions one would seek the opinions of dedicated domain experts, the results of the methods would still exhibit a certain amount of subjectivity. Apart from potential flaws or drawbacks of the applied design methodology, this is also highly due to cognitive biases. Such human biases rely on judgmental heuristics and help people make intuitive decisions in uncertain situations (Tversky & Kahneman, 1974). However, these can lead to systematic errors, especially when addressing complex tasks such as seeking innovative designs for new product generations. These drawbacks of subjective techniques for idea generation could result in the following unwanted outcomes:

a) the designers might rely mostly on their previous experience;
b) prioritization of known or existing problem solutions rather than innovative ideas;
c) the objectively optimal solution for a given problem statement may unwillingly be left out of scope.

In order to avoid these potential pitfalls, an increased level of automation of conceptual design processes could be sought. As shown in Figure 1, this could be addressed during the conceptual design stage by introducing software for Computer-Aided Innovation (CAI) purposes. Kohn and Hüsig (Kohn & Hüsig, 2007) classify CAI tools into the categories Strategy Management, Idea Management and Patent Management. The creation of innovative products as solutions for unconventional or complex problem statements falls under the Idea Management class. It can be further divided into the sub-categories' idea generation, idea collection (search and integration of existing problem solutions), idea evaluation and idea classification.

For the reasons mentioned in Section 2, full automation of conceptual product design can hardly be achieved. In order to profit from computational capabilities, it is therefore necessary to introduce software covering all sub-classes of Idea Management while making it a proper aid to the designer and combining computational advantages and expert human reasoning. In this context, one could define global initial purposes/requirements for such software as follows:

a) extended automation of conceptual design tasks in the fields Idea Generation, Idea Collection, Idea Evaluation and Idea Classification;
b) robust formalization of problem structuring regardless of application domain;
c) transparent and intuitive algorithm and execution;
d) efficient and intuitive interaction between the software and the experts/designers;
e) reduction of human cognitive biases in the design process;
f) handling of possible uncertainties;
g) consideration of the multidisciplinary character of conceptual design;
h) ability to generate, evaluate and classify innovative technologies with partial or complete lack of experimental or statistical data.

The sub-category idea evaluation implies the use of structured evaluation techniques and/or the involvement of expert systems for the ranking or comparison of alternative design ideas. For this purpose, one could apply certain Multiple-Criteria Decision-Making (MCDM) methods, which represent sets of mathematical tools used for ranking, sorting, describing or narrowing down given sets of alternative scenarios (Mota et al., 2013). These approaches allow certain structuring and a mathematical framework for the decision-making tasks while considering multiple evaluation criteria simultaneously. MCDM methods can be divided into Multiple-Attribute Decision Making (MADM) and Multiple-Objective Decision-Making (MODM) categories, depending whether the evaluations are conducted on discrete or continuous variables respectively (Mota et al., 2013).

A study of available CAI tools conducted by Zaripova and Petrova (Zaripova & Petrova, 2012) has revealed that the majority of idea generation software relies mostly on the brainstorming and mind mapping techniques. However, the authors of the source underline that these methods are less effective for addressing complex engineering design tasks. In the same time, they suggest the MA as a more suitable approach among other ones. According to the study results, there is a very limited amount of software products which implement the method.

4. Morphological Methods

Along with the estimated higher effectiveness for idea generation, the Morphological Analysis (MA) is also considered as the most commonly used method among the discursive techniques for structural synthesis (Zwicky,1969), (Levin, 2015). Thus, according to statistics compiled in 2009 by German scientists, the total number of companies using the morphology is more than 40%, while regular use is done by more than 20% (Smerlinski et al., 2009). Morphological synthesis is regarded as a methodology to streamline the problem to be solved. Morphological analysis is a method developed by F. Zwicky for exploring all the possible solutions to a multi-dimensional, non-quantified problem complex (Zwicky,1969). Zwicky applied this method to such diverse tasks as the classification of astrophysical objects and the development of jet and rocket propulsion systems. More recently, morphological analysis has been extended and applied by a number of researchers in the USA and Europe in the field of future studies, engineering system analysis and strategy modelling.

The MA envisages the decomposition of the product to be designed into multiple constructive, functional or technological elements (Zwicky,1969), (Garvey, 2016). Subsequently, one assigns to each element a finite set of alternative design solutions. All possible combinations of alternative technology options for each element compose the solution space for the given design problem.

Most discursive approaches for structural analysis and synthesis of engineering solutions are based on morphological models, which exhibit the following disadvantages in this case: the enormous volume of the morphological set of solutions, the problems of choosing rational options and their interaction with the external environment (Zwicky,1969). The power of the morphological set can reach millions of possible solutions. In general, classical morphological models are inappropriate for large parameter studies, such as the optimization of flight systems.

At present, there exist many methods to search and synthesize solutions based on the morphological analysis in a variety of physical and engineering areas (Pereverza et al., 2017; Ritchey, 2018).

Some of the largest problems of application of classical methods of morphological analysis are: poor access to software support necessary to address the combinatorial explosion generated by multi-parameter problem spaces inherent in the use of MA; insufficiently flexible processes addressing users' operational constraints; perception of being overly generic, disguising identification of specific application areas of interest (Garvey, 2016).

A major step to address these challenges and the CAI tool requirements outlined in Section 3 could be seen in the developed Advanced Morphological Approach (AMA) (Rakov 2019,2020), (Bardenhagen & Rakov, 2019). It is based on the provisional MA, system analysis, variant clustering and mathematical modelling. Among others, AMA's main features include:

a) intuitive implementation of the MA methodology;
b) filtering of solutions with incompatible technological options;
c) qualitative multi-criteria evaluation of options by dedicated experts;
d) integration of existing products as reference design problem solutions;
e) clustering of the obtained solutions based on their evaluation scores.

Therefore, the AMA approach aims to cover all sub-categories of Idea Management, namely idea generation, idea collection, idea classification and idea evaluation.

As a result of all mentioned actions, the designer obtains a visualized design space with ranked and highlighted clusters and solutions along the axis of the defined criteria. Example results of such visualizations are presented in Figures 2,3 and 4. This serves as a clear overview of the available solutions and therefore as a direct decision-making aid on the most suitable product concept. It is worth noting that the qualitative evaluation and clustering of solutions allows to include innovative technologies with lack of prior statistical or experimental data. Thus, the AMA represents an example of potential long-term designer benefit from purposeful CAI tools. Furthermore, it also motivates to use non-conventional and novel technological options in the search for breakthrough solutions.

Nevertheless, not all requirements for the desired CAI conceptual design tool from Section 3 have been met within the AMA. Particularly, the consideration of uncertainties and multidisciplinary evaluation should be introduced as future improvement.

Very often in the practice of project management there is a task of forecasting the development of the objects under study.

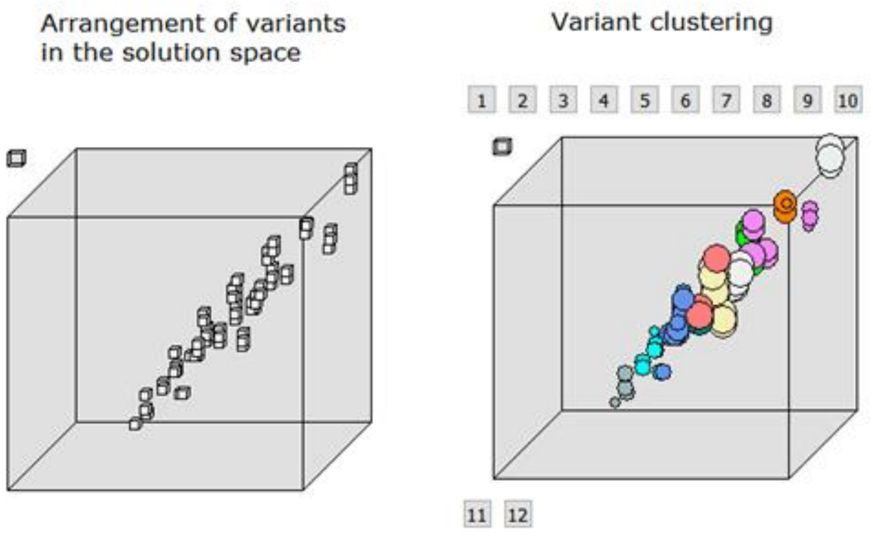


Figure 2. Arrangement of variants in the solution space, clustering of variants

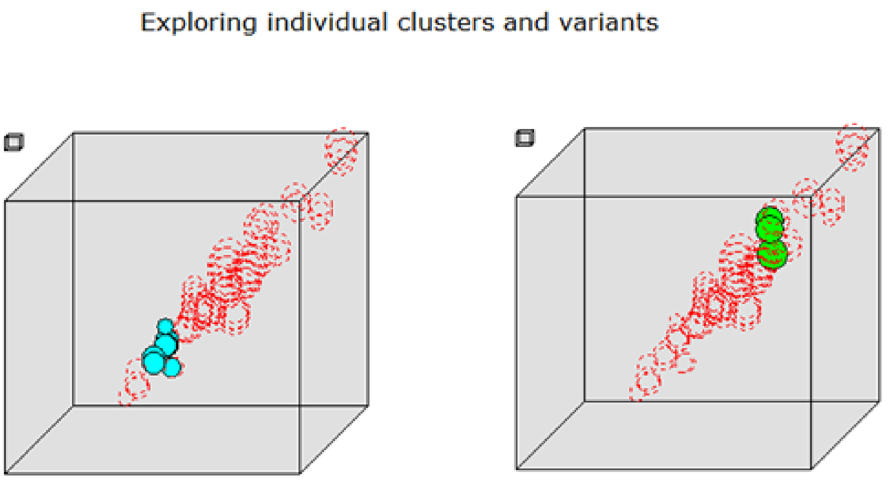


Figure 3. Investigation of clusters in the solution field

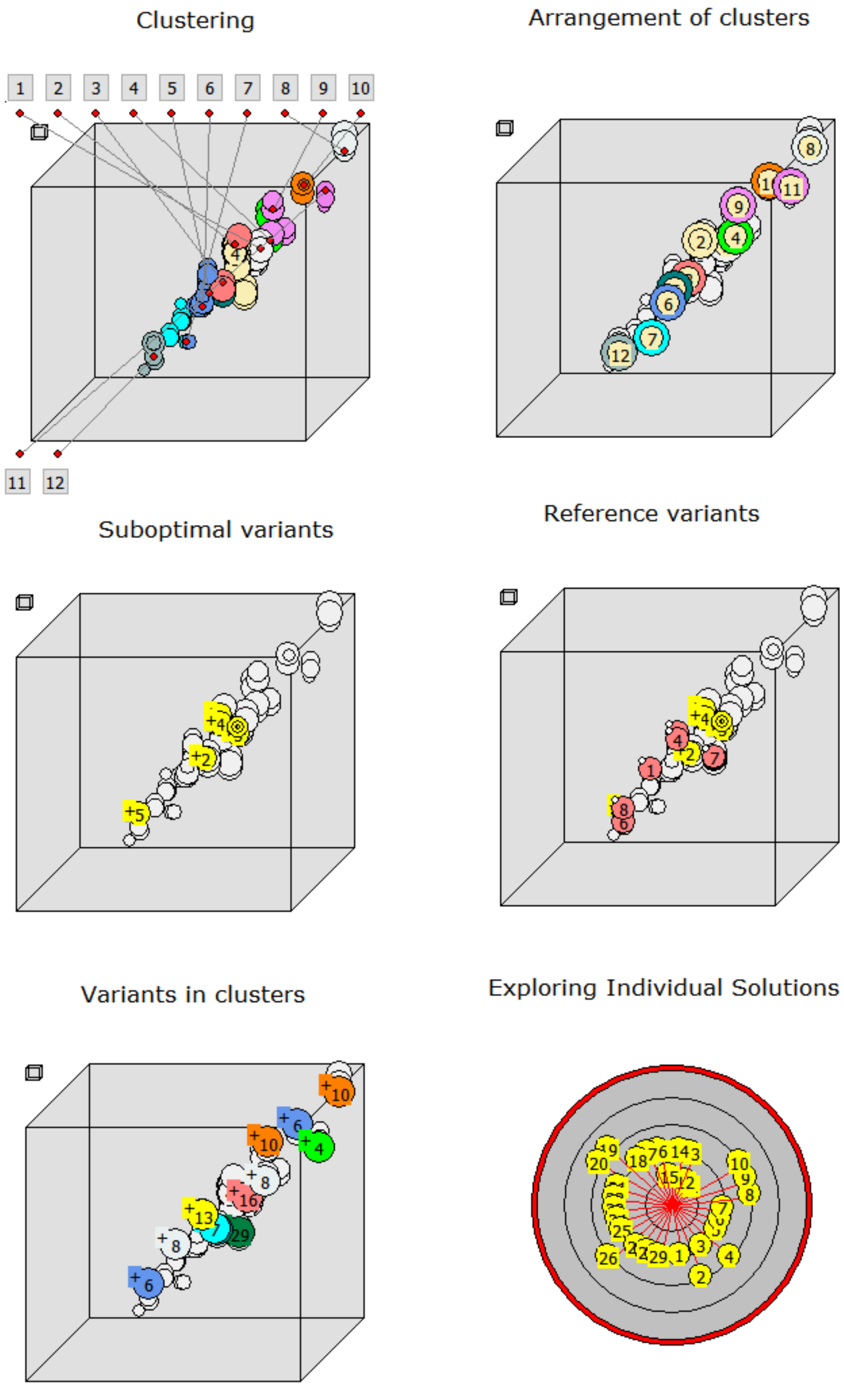
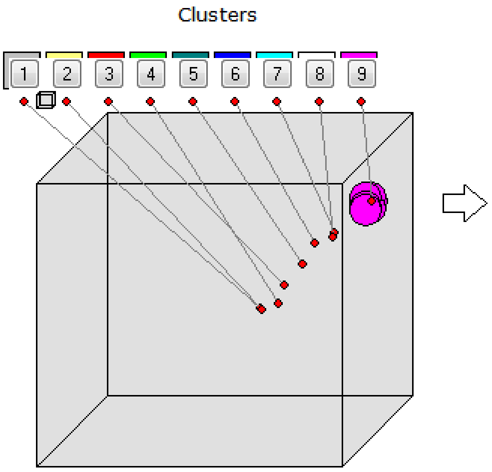


Figure 4. Exploring clusters and individual cluster solutions

5. Results

As the result, a search for engineering solutions for micro-arc oxidation is given (Rakov et al., 2018). Microarc oxidation is an electrochemical process of oxidation of the surface layer of valve metals and alloys combined with electric discharge phenomena at the anode - electrolyte boundary. A morphological matrix with the following features - coating modes, electrolytes used, materials used, coating process control, frequency control, etc. - was generated to synthesize and evaluate the variants. Any set of elements of all traits represents a possible technology option. After synthesis, a cluster was selected and a number of technical solutions were scanned (Figure 5). An experimental setup was created for the rad solutions and the coatings were synthesized (Figures 6 and 7).



		1	2	3	4	5	6	7	8	9		
1		1	1	1	2	1	2	1	3	2	1.11	1.15
2		2	2	1	1	2	3	1	2	2	1.53	1.14
3	1	2	2	1	3	2	1	1	2	1	1.79	1.14
4	3	2	2	1	3	2	2	1	2	3	1.82	1.14
5	6	2	2	1	3	1	1	1	2	3	1.82	1.15
6	7	1	1	1	3	1	1	1	2	1	1.56	1.16
7	8	1	1	1	3	1	1	1	2	2	1.59	1.16
8		2	2	1	3	2	1	1	2	3	1.87	1.14
9		1	2	1	3	2	2	1	2	3	1.76	1.15
10		2	2	1	3	2	3	1	2	3	1.79	1.14

Figure 5. Location clusters in the morphological field of solutions

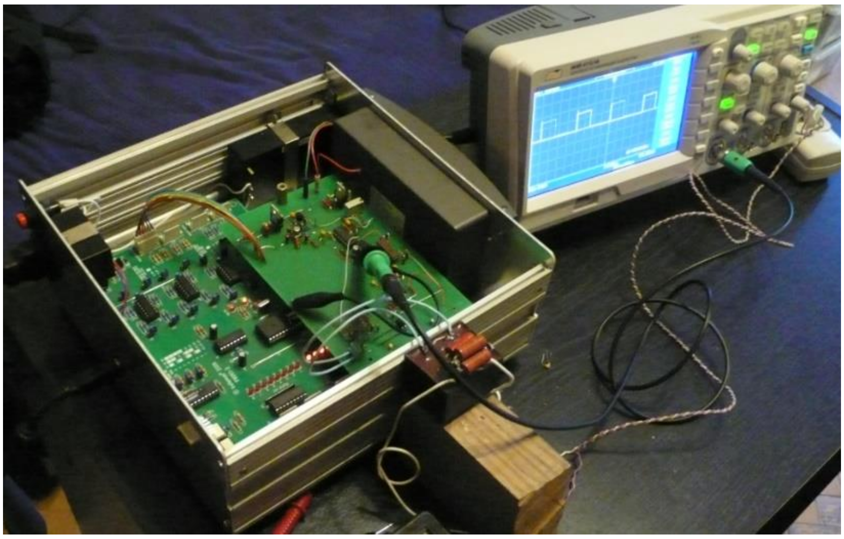


Figure 6. Experimental installation

Figure 7. Research specimen with ceramic coatings

6. Discussion and Conclusions

The article discusses formalization and automation aspects of idea management for novel engineering and technological solutions. First, attention is drawn to some issues associated with approaches relying purely on human estimations and experience. In particular, methods like brainstorming and mind mapping face cognitive bias from human reasoning and could result in unwanted outcomes such as sub-optimal problem solutions and unexplained uncertainties. These phenomena could be reduced by increasing the level of automation in idea management, namely for idea generation, idea collection, idea evaluation and idea classification. In order to approach the development of CAI software which covers all these areas, the current article defines global purposes and requirements for such tools. Since morphological approaches are more suitable for the conceptual design of complex engineering solutions, the MA is introduced through its applications and capabilities.

In this context, the Advanced Morphological Approach was given as a specific example which aims to cover the full spectrum of idea management tasks during conceptual design of complex engineering solutions. However, it still exhibits necessity for further improvements in order to cover the defined requirements, such as multidisciplinary interactions and evaluations and improved problem structuring.

The main automation challenges include the creation of approaches that allow early processing of information flows and produce some set of possible solutions. In focus lies the efficiency improvement of design studies and the reduction of time spent on the entire process creation cycle. The introduction of such a software tool would allow to generate a space of feasible solutions. Ideally, these solutions would be resistant to changes in the external environment and therefore have high competitiveness.

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References

Aliyev, A., & Shahverdiyeva, R. (2017). Technical Ideas and Knowledge into Innovations in Technoparks. I.J. Engineering and Manufacturing, 2017, 2, 1-10.

Bardenhagen, A., & Rakov D. (2019). Advanced morphological approach in aerospace design during conceptual stage. Facta Universitatis,17(3), 321-332.

Boutemedjet, A., Samardžić, M., Rebhi, L., Rajić, Z., & Mouada, T. (2019). UAV aerodynamic design involving genetic algorithm and artificial neural network for wing preliminary computation. Aerospace Science and Technology, 84, 464-483.

Park, C., & Lee, D. (2020). Analysis on new types of electric power businesses using a morphological box. Energy & Environment. 32 (1), 113-133.

Garvey, B. (2016) Combining quantitative and qualitative aspects of problem structuring in computational morphological analysis. PhD thesis, Imperial College London.

Geng, X., Chu, X., Xue, D., & Zhang, Z. (2011). A systematic decision-making approach for the optimal product-service system planning. Expert Systems with Applications, 38 (9), 11849–11858.

Gost 2.118-2013. (2013) Unified system for design documentation. Technical proposal.

Hashimova, K.K. (2016). The Role of Big Data in Internet Advertising Problem Solution. I.J. Education and Management Engineering, 2016, 4, 10-19.

Isenmann, R., Landwehr-Zloch, S., & Zinn, S. (2020) Morphological box for ESD – landmark for universities implementing education for sustainable development (ESD), The International Journal of Management Education, 18 (1).

Kohn, S., & Huesig, S. (2007). Development of an empirical-based categorisation scheme for CAI software. International Journal of Computer Applications in Technology, 30(1/2), 33-46.

Knolmayer, G., & Borean A. (2010) A Morphological Box for Handling Temporal Data in B2C Systems. In: Cellary W., Estevez E. (eds) Software Services for e-World. I3E 2010. IFIP Advances in Information and Communication Technology, 41.

Komenda, T., Steiner, M., Rathmair, M., & Brandstötter M. (2020). Introducing a Morphological Box for an Extended Risk Assessment of Human-Robot Work Systems Considering Prospective System Modifications. Proceedings of the Joint Austrian Computer Vision and Robotics Workshop, Graz. JRROB-20-RAT-1.

Levin, M. (2015). Modular System Design and Evaluation, Decision Engineering, Switzerland: Springer International Publishing.

Mishin, V.P., & Osin, M.I. (1978). Introduction to Aircrafts Machine Design, Moscow: Mashinostroenie.

Mota, P., Campos, A. R., & Neves-Silva, R. (2013). First Look at MCDM: Choosing a Decision Method. Advances in Smart Systems Research, 3(2), 25–30.

Nakao, K. (2001). A planning methodology of systems technologies by a normatively developed morphological box. IEMC'01 Proceedings. Change Management and the New Industrial Revolution. IEMC-2001, 440-445.

Pereverza, K., Pasichnyi, O., Lazarevic, D., & Kordas, O. (2017) Strategic planning for sustainable heating in cities: A morphological method for scenario development and selection. Applied Energy, 186, 115-125.

Rakov, D., Sukhorukov, R., & Pecheykina, M. (2018). Computer-aided innovation support system based on the morphological approach. Journal of Machinery Manufacture and Reliability, 48, 173-178.

Rakov, D. (2010). Structural analysis and synthesis of new technical systems on the basis of morphological approach, Moscow: Librokom.

Rakov, D. (2019). Okkam - advanced morphological approach as method for computer aided innovation (CAI). MATEC Web of Conferences 298, 00120.

Rakov, D. (2020). Advantages and disadvantages of morphological methods in engineering. MATEC Web Conf., 329, 03028.

Rao, R. (2007). Introduction to Multiple Attribute Decision-making (MADM) Methods in Decision Making in the Manufacturing Environment: Using Graph Theory and Fuzzy Multiple Attribute Decision Making. Springer.

Ritchey, T. (2018). General morphological analysis as a basic scientific modelling method. Technological Forecasting and Social Change. 126, 81-91.

Smerlinski, M., Stephan, M., & Gundlach C. (2009). Innovationsmanagement in hessischen Unternehmen. Eine empirische Untersuchung zur Praxis in klein- und mittelständischen Unternehmen. Discussion Paper on Strategy and Innovation, Marburg.

Späker, L., Mark, B., & Rauch, E. (2021). Development of a Morphological Box to Describe Worker Assistance Systems in Manufacturing. Procedia Manufacturing. 55,168-175.

Thielman, J., & Ge, P. (2006). Applying axiomatic design theory to the evaluation and optimization of large-scale engineering systems. Journal of Engineering Design,17 (1), 1–16.

Tversky, A., & Kahneman, D. (1974). Judgment under Uncertainty: Heuristics and Biases. Science, 185(4157), 1124–1131.

Witt, T., Stahlecker, K., & Geldermann, J. (2018). Morphological analysis of energy scenarios. International Journal of Energy Sector Management, 16(2), 116-125.

Xu, Zeshui. (2015). Uncertain Multi-attribute Decision Making Methods and Applications. Springer.

Zaripova, V., & Petrova, I. (2012). Model of development of computer aided innovation tools (CAI). Prikaspiskii Journal, 3(19), 111–129.

Zhu, M., Zhang, S., & Zheng, Y. (2018). Conceptual design and optimization of scramjet engines using the exergy method. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 40(12), 553.

Zwicky, F. (1969). Discovery, Invention, Research – Through the Morphological Approach, Toronto: The Macmillan Company.