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IMPROVING DESIGN METHODOLOGY: SYSTEMATIC EVALUATION OF PRINCIPLE SYNTHESIS

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Abstract

Developing new products based on a systematic approach is essential for the entrepreneurial success of technology companies. Through functional analysis and successive synthesis of a product reformative solutions can be generated. The paper in hand reviews existing methods and illustrates the occurring hurdles and advantages. Commonly used, the morphological box with its inevitable and hardly manageable large number of theoretical solutions resulting from combinatorial explosion is investigated. To overcome those drawbacks, a new software-based method for stepped synthesis is presented which integrates existing knowledge about physical principles and an evaluation algorithm. The applicability of this new method is evaluated in a student survey using a software prototype.

Keywords: Computational design synthesis, Decision making, Design methodology, Evaluation, Early design phases

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1 INTRODUCTION

Creating new products in a systematic way has been the focus of design methodology throughout the last decades. Market conditions become more contested due to globalisation and customers' wishes for newer products in ever shortening time spans. Engineering departments are forced to accelerate their innovation cycles and develop reliable products with limited resources. Thus, methodical approaches become more relevant and have to be integrated in today's education of future design engineers. One promising method is the functional decomposition with a succeeding recomposition of the elaborated solutions. Literature refers to this approach as principle synthesis (Pahl *et al.*, 2007). Section 2 thus revisits the state of the art of principle synthesis within the early phases of product development processes with special attention on curricular feasibility. Separate subsections address its significance regarding New Product Development as well as analysis and synthesis characteristics of the method. The third section presents the new and integrated approach that bases on both the integration of specific engineering knowledge and an intermediate direct assessment to ensure high quality solutions. An accompanying software demonstrator is presented in the fourth section before the paper concludes.

2 STATE OF THE ART OF PRODUCT PRINCIPLE SYNTHESIS

2.1 New Product Conception

Pahl and Beitz introduced a model that links individual activities during a product planning and design processes systematically and maps them with additional consideration of a time component within a definite course of action (Fig. 1). This process consists of four main phases starting with the assignment of the task and ranging to the solution, while the course allows unavoidable iterations in practical use (Pahl *et al.*, 2007).

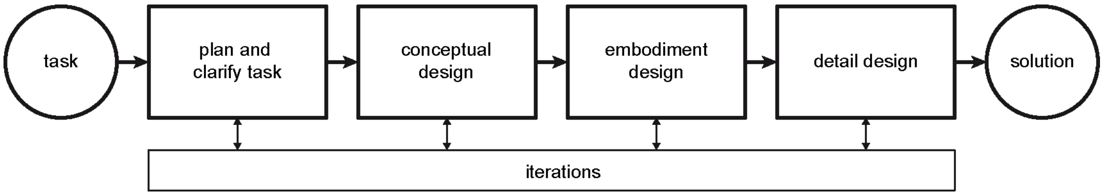

Figure 1. Planning and design process according to Pahl and Beitz (Pahl et al., 2007)

At first detailed requirements for the result are derived from the task as the ignition point of the process. In the subsequent phase essential functions are identified from these requirements. Those functions are comparatively easy to realise after a structured decomposition in sub-functions and the use of established partial solutions. The number of potential combinations of partial solutions leads to a multiplicity of concepts. The comparison of separate concepts with each other using an evaluation of definite aspects enables the determination of one concept that is to be concretised in the following phase of embodiment design. In the closing phase details of the design are defined and working results are documented in order to hand over the solution as the result of the process to manufacturing.

2.2 Functional analysis and decomposition

Every technical system features one main purpose. The whole system is to be designed to fulfil this scope. As presented by Suh in his Axiomatic Design theory, the transformation of predefined requirements into feasible solutions in a methodological way leads to well-structured designs of technical systems (Suh, 2001). The author introduces four different domains, whose correlations are covered by matrices and mathematical operations. The second domain covers so called Functional Requirements which can be regarded as functions in the understanding of this paper. The main purpose of a technical system can be described by an overall function. As most technical systems involve a certain complexity to realise the desired operation, the overall function itself can be divided into further sub-functions. Each sub-function represents a certain, detailed fragment of the general technical solution. The more sub-functions can be identified, the more precisely the technical system is described. According to Pahl, this procedure of decomposition is called the functional analysis (Pahl *et al.*, 2007). According to Koller, the breakdown of functions into sub-functions ends with elementary technical operations that cannot be divided any further (Fig. 2). Those operations are called elementary functions. Their technical content is not bound to a specific problem but can be used for general implementations. Elementary functions have been thoroughly investigated by Koller and Kastrup (Koller and Kastrup, 1998). While most design tasks in the field of mechanical engineering are too complex to be directly solved by engineers, the approach of elementary functions enables the user to precisely identify manageable sub-tasks. Physical effects are utilised to achieve those tasks. Koller states, a technical function is describable as the realisation of one activity with physical variables as input and the same or another variable as output (Koller, 1998).

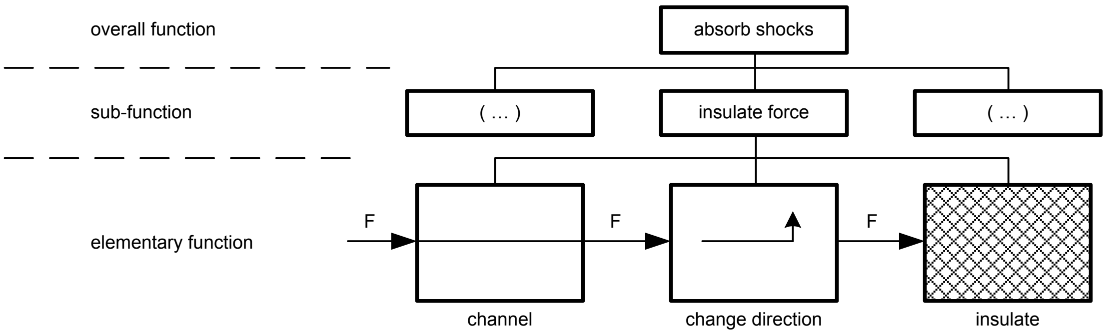

Figure 2. Functional decomposition using elementary functions

In contrast to the methodologies of Koller and Pahl, the function-behaviour-state model (FBS) of Umeda et al. focusses on the different aspects of physical effects depending on the engineering viewpoint (Umeda *et al.*, 1990). The FBS method proposes the integration of sub-functions into one principle solution. Unfortunately, FBS does not define clear criteria for the integration of knowledge databases. As the approach presented here concentrates on the identification of elementary functions suited for the design task while relying on user-independent knowledge databases, FBS is not integrated into the mentioned methodology. Besides the discussed approaches, a comprehensive overview of product development methodologies and the use of function concepts in particular are given by Tomiyama (Tomiyama *et al.*, 2009).

2.3 Principle solution synthesis

As with all approaches that split up larger and initially unsolvable problems into smaller ones that are manageable, at some point, the granularly developed solutions have to be recombined to build a complete solution that fulfils the previously defined purpose. Although the described methods are widely adopted and meticulously described by their authors, most of them do not address this essential synthesis step at all or refer to combination approaches like morphological analyses. Instead, they directly focus on the process of finding a Gestalt. This leaves teachers and students alike in an uncomfortable position. For example, Koller does not address the synthesis explicitly, but refers to a not further detailed step of necessary combination of the single solutions (Koller, 1998). For every elementary function with determined physical values as input and output, principle technical solutions can be found, e.g. usage of the lever effect to increase a mechanical force. The more solutions to each elementary function can be found, the more solutions can be created by combining several principle solutions to complex products. One possible synthesis method within this approach is the morphological box, where principle solutions are structured in matrix form and the overall solution can be found by combining single solutions from different sub-functions. This systematic combination of single elements using the concept of morphological analysis has been introduced by Zwicky (Zwicky, 1969). Most universities still teach the morphological box as the panacea to all problems related with the synthesis step although its intrinsic and ill-fated character of producing a vast amount of possible solutions that neither students nor engineers in industry are capable to investigate. Moreover, the morphological analysis often is used to justify the preferred solutions of the operator without investigating the complete solution field, which renders the initial approach of the method useless (Tomiyama *et al.*, 2009).

2.4 Discussion of existing synthesis methods

Having various methods for recombination increases the potential of conceiving innovative products (Ponn and Lindemann, 2011). However, the amount of possible solutions is dramatically rising by the number of solutions for each sub-function. These circumstances aggravate by the search for unknown principle solutions performed by the design engineer in order to discover new innovative concepts. The more principle solutions are found, the more solutions arise. This effect is commonly referred to as combinatorial explosion. To overcome this problem, various synthesis approaches exist: Ponn addresses the compatibility of principles in regard of their combination which can be determined before the actual combination is noted in a table called compatibility-matrix. Thus incompatible solutions are not to be combined with each other, e.g. due to incompatible physical values (Claussen, 1971). While generating combinations of principle solutions, the combination of two solutions can be evaluated immediately after being set. Thereby the complexity of screening the most attractive solutions can be significantly reduced. However, innovative solutions may be found within unattractive combinations of single principle solutions as well, which is not respected within this approach presented by Birkhofer (Birkhofer, 1980). Schneider proposes the assessment of generated solutions executed by a group of design engineers that is based on the selective usage of expert knowledge and can be used to reduce the amount of possible solutions. The most attractive principles are preselected out of the collective of principle solutions. Afterwards, implementation concepts are built with the selected principle solutions to fulfil the product's overall function. The result quality of this approach depends on the existing expert knowledge (Schneider, 2001). Besides the analysis of technical compatibility of principle solutions, a selection based on technically and economically favourable solutions in regard of efficiency has been reported useful by Pahl (Pahl *et al.*, 2007). Based on the product requirements and the estimation of expenses only those concepts shall be pursued, that are expected to be economically attractive. Every single solution has to be evaluated according to the same criteria. The assessment of principle solutions is limited to the associated sub-function, which implies that only solutions of the same function are evaluated among each other. For each sub-function, favourite principle solutions have to be selected. The most attractive overall solution has to be evaluated furthermore. According to Pahl, the reasons for the selection of principle solutions and overall solutions as well have to be documented clearly and comprehensible. The evaluation is done within a special form called systematic selection chart (Pahl *et al.*, 2007). All presented methods utilise the exclusion of several principle solutions to find the optimum overall solution. Within all presented assessment procedures, a negative assessment of single principle solutions leads to their exclusion from the set of overall solution combinations. Here, the fact is neglected that a certain combination of inferior principle solutions might represent a good overall solution as well. Another disadvantage of those approaches lies within the static evaluation criteria that are used for the assessment of the principle solutions. In times of accelerated development processes and rapid technological progress a task-sensitive assessment of principle solutions seems more suitable. Due to the claim of general applicability, the presentation of the principle solutions lack of concrete examples and existing application references.

3 INTEGRATED SYNTHESIS APPROACH

To overcome this unsatisfying situation, a new integrated method for the systematic synthesis of principle solutions is proposed. It is based on the functional product description introduced by Koller using elementary functions and physical effects (Koller, 1998). By incorporating knowledge about the effects and typical examples for their use in existing products, it is made easier for students to apply the method during education. A newly conceptualised assessment approach secures the limitation of the number of automatically suggested combinations that have to be further analysed by engineers.

3.1 Specific knowledge integration

In addition to the usage of physical effects and their general technical application introduced by Koller, the presented knowledge has been complemented by integrating specific intelligence to each proposed technical solution. The additional set of information enables the user to evaluate the suitability of the presented physical effect and its technical application for the actual use case. While the descriptions of the physical effects presented by Koller offer basic scientific information, the added data provides more application-oriented material (Apfel, 2012).

3.2 Direct assessment of principle solutions

Combining the functional product description and the integration of specific knowledge proposed by Apfel, sub-solutions can be determined as appropriate elements of an overall solution concept that provides a technical mechanism to solve the given problem (Apfel, 2012). Although the final solution is based on several sub-solutions, the discovery of appropriate combinations in terms of best matching mechanisms is challenging for the operator of the method. To facilitate this process, a method of direct assessment of sub-solutions has been created (Katzwinkel, 2013). Within this method, the overall evaluation criteria and their possible values are determined across projects while the evaluation of each principle solution is performed individually within every single design task. The overall criteria and their values provide the missing objectivity (cf. sec. 2.4) within the evaluation process. At the same time, the individual evaluation process enables product developers to refer to the requirements implied by the current design task (e.g. manufacturing restrictions, economic boundary conditions or legal limitations). Afterwards, the combination of several principle solutions is rated according to the sum of their single values referring to the determined criteria. The overall solutions can be classified by the value of single criterions or weighted combinations of several criteria. Hence, all possible combinations can be evaluated in a context sensitive way. The criteria are declared application specific, depending on the content of the catalogued knowledge. Katzwinkel elaborated the following criteria as suitable in the context: action principle (evaluates the functional performance of principle solutions), degree of innovation (expresses the newness of principles according to the given task), safety (refers to the grade of safety concerning principle solutions) and economic effort (considers the expected effort in design and manufacturing a product implementing the presented principle solution) (Katzwinkel, 2013).

4 SOFTWARE BASED DEMONSTRATOR

To validate the applicability of the presented approach, a software tool has been conceived by Müser (Müser, 2011). As proposed by Apfel, the information to each principle solution have been enhanced by including the reachable magnitude of the used physical effect (e.g. force amount) and examples of existing technical products that already implement the presented effect, which has been reflected in the software tool as well (Apfel, 2012). All principle solutions presented by Koller and Apfel are stored and made accessible in a common database.

At the beginning of a new design task, the design engineer has to perform a functional analysis and decomposition down to the level of elementary functions. To make the analysis more comfortable, the user is supported by a graphical function structure editor within the software (Fig. 3). Based upon this structure, a user-driven database query is performed to determine suitable principle solutions. Afterwards, every principle solution has to be rated according to fixed criteria. When the assessment of all presented principle solutions is conducted, the software presents all mathematically possible combinations in a list, which can be sorted by the value of one criterion or a weighted combination of different criteria. In that way, the most suitable overall solution is assumed to be within the group of list entries featuring the highest ranks.

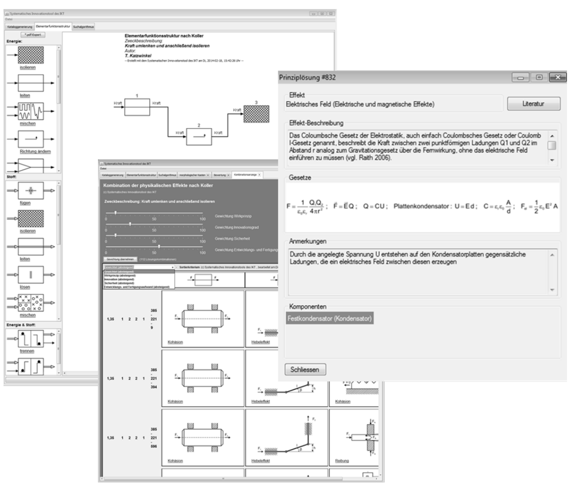

Figure 3. Screenshots of the software demonstrator

5 EXEMPLARY APPLICATION DURING STUDENT SURVEY

The effectiveness of this software regarding the synthesis step and the assessment algorithm has been validated in a research project with eight systematic engineering design students, having recently graduated. The setting consisted of seven male students and one female student with an average age of 30 years. The database of the software contained 1.266 different principle solutions. The database knowledge is organised conforming to the works of Koller (Koller, 1998). Within this study, the given task was to redesign a concept for a single-staged spur gear by using one combination of exactly three elementary functions. The hypothesis was to reduce the evaluation effort of combinations of principle solutions significantly by applying the approach of direct assessment of sub-solutions. To measure the efficiency of the integrated synthesis approach presented in Sec. 3, the amount of suitable combinations of principle solutions before and after the evaluation process has been recorded and compared. Therefore, the students had to evaluate every principle solution presented to them by the database. Their favourite solution had to be indicated manually. Afterwards, the individual evaluation values have been entered into the software. The ranking of the students' favourite solution within the list of overall solutions has been recorded beginning with the entry having the highest value, in order to compare the amount of necessary analysis steps to identify the preferred solution by gradually excluding the best rated overall solutions. The detailed results of the evaluation are shown in Fig. 4.

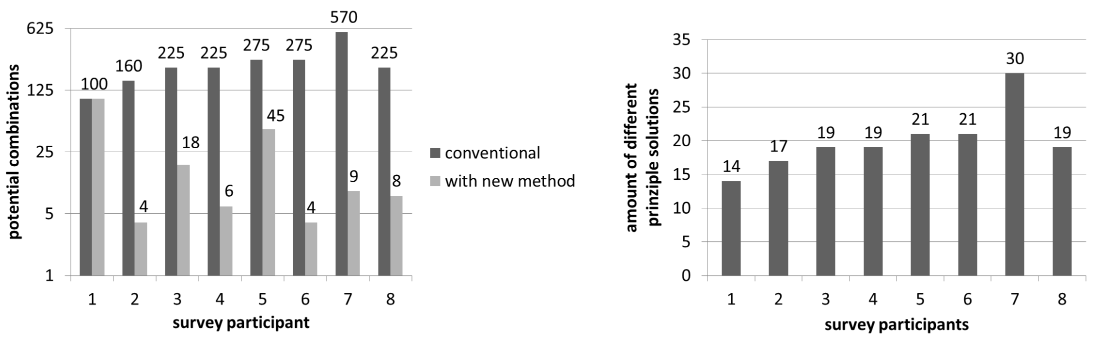

Figure 4. Evaluation of the present study

After combining three elementary solutions, the average amount of potentially suitable principle solutions found by the database query counts 20 principle solutions (1.6 % of the overall database). The average amount of possible combinations out of those principle solutions was approximately 256 overall solutions. During the evaluation process the average amount of combinations that had to be analysed in order to find the preferred solution settled by the students could be reduced by as much as 90 %. On average, after analysing only 25 overall combinations the preferred solution was found systematically by following the methodology of direct assessment of principle solutions.
Considering the results of the study, the presented approach has been validated useful for the significant reduction of variety within the principle solution synthesis. In addition to the reduction of expenditure, the overall amount of solutions has not been cropped by excluding single principle solutions within the presented methodology. Combinations of low rated single principle solutions that might have turned out attractive only within their combination with each other, are still included in the combination list. By applying the presented methodology, no combination of principle solutions is lost during the evaluation process (cf. sec. 2.4). In addition, the initial hypothesis could be verified.

6 CONCLUSION AND OUTLOOK

In this paper, a new approach for systematic principle synthesis in engineering design is presented. The discussed methodology is based on the catalogue of principle solutions proposed by Koller (Koller, 1998). Specific knowledge has been added to the database in order to enhance the applicability of this design methodology. Regarding the systematic principle synthesis, the disadvantages of existing approaches have been diminished by the direct assessment of principle solutions and a new sorting scheme of solution combinations. A software based demonstrator was generated to proof the functionality of the presented method. The efficiency of the integrated synthesis approach has been measured in an evaluation in academic context. It was found that the approach works efficiently.

The presented findings are part of a larger-scale research project at RWTH Aachen University. The intention of this research project is the individual, software-based methodological support of product development in industry and academia. Regarding the presented approach, future steps are the further refinement of the tool as well as the investigation of the underlying method considering its principle feasibility for more complex day-to-day industrial applications. Finally, the software will be used in curricula to enhance the academic training in engineering and product design education.

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