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A METHODICAL APPROACH FOR DESIGNING INNOVATIVE PRODUCTS BASED ON COMPUTER AIDED FUNCTIONAL MODELLING

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ABSTRACT

Creating innovative products is vital for the success of enterprises. Markets change constantly and force engineering departments to shorten innovation cycles. To be competitive, a methodical approach for systematic innovation is needed. One promising way to achieve this goal is to base development processes on functional modelling. In this paper, an overview of existing functional modelling approaches is laid out and advantages as well as disadvantages are discussed. Koller's methodology is presented in detail as it is highly suitable for systematic innovation. Although several methods seem to be published and well-documented, they currently are not widely adopted in industrial use. Reasons for this shortage are elaborated. An improved methodology for working with functions, physical effects and the morphological box is introduced. Different single aspects like disadvantages with the paper-based use of effect catalogues or the incorporation of magnitude influence with the composition of physical effects are shown. An implementation of a software prototype and its evolution is given. Thoughts on further improvement of both methodology and tool conclude the paper.

Keywords: innovation, functional modelling, conceptual design, early design phases, design process

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1 INTRODUCTION

Not only since 2009, when the European Year of Innovation was proclaimed, innovation is a key factor for the success of enterprises. It is vital for enterprises in constantly changing markets – a fact that is elaborated conjointly in relevant publications. (Disselkamp, 2005; Stern, 2010). But the exclusive concentration on the *effectiveness* of the innovation process and thus the product development processes – i.e. the development of the *right* products – is not sufficient (Schuh, 2008). Furthermore, the *efficiency* of the innovation process gains more significance through changing constraints that result from shorter economic product life cycles as market presence phases shorten. That leads to faster and more frequent innovation cycles, enlarged product variance and increased product complexity (Jäger, 1995; Kurz, 2004; Pahl et al., 2007; Schuh, 2008). Thus, enterprises need to turn innovative *product ideas* into *actual products* being available on the market within short time spans featuring competitive prices and still fulfilling customers' requirements (Pahl et al., 2007; Wheelwright 1992). One critical factor of success is the time needed for the innovation process. Its importance becomes apparent when looking at the large percentage that product development processes usually take of the overall new product launch phase (time-to-market) (Pawar, 1994).

Basis for the desired efficient innovation process, which is comprised of the product planning as well as the product development phase according to Geschka (2007), is a methodical approach covering both phases. In the field of the latter such methodologies are for instance published by Koller (1998) and by Pahl and Beitz (2007). Several further approaches are conjointly published in the VDI guideline 2221 (VDI, 2221). All steps of the methodologies are supported by methods and tools.

Concluding, a systematic and reproducible approach for product development is needed today more than ever. One way to deal with the complexity of modern products is the use of methods that abstract the problem to a level on which it is manageable. The modelling of functions seems to be one appropriate way to achieve that. By using it, it is possible to conceive innovations by systematic variation of the physical effects underlying the elementary functions of the concept.

Section 2 of this paper presents an overview of different approaches already published. Picking up from there, the details of Koller's methodology and its application in engineering design processes are laid out in section 3. The fourth section starts with discussing advantages and disadvantages of the presented methodology, presents two iterations of a software tool and draws conclusions leading to suggestions how to improve the use of function-related software. An outlook is given in section 5.

2 STATE OF THE ART

2.1 Functions in Product Development

Functions are an appropriate means of describing the elements customers request in products. Typically, new product development for engineering departments begins with the collection of requirements. Their well-structured compilation is called requirements list. The next step is the formulation of functions; either directly transferred from one specific requirement or brought together by taking several requirements into account. Often, customers directly express which functions they want in a product. In most cases, they can easily tell, that they desire a specific function to be present in a product. (E.g. customers may want to have the ability to adjust the cutting depth of a lawn-mower. So it is easy to formulate the function *adjust cutting depth*.) However, for the customer it is more difficult or even impossible to directly express, which components need to be present in a product to fulfil that function. (E.g. customers usually do not know how the adjustment mechanism works and which components realise that function. In case of a new product, design engineers may also not know about the mechanism yet, however, several methods exists (see section 2.2) that support turning those functions into actual products or product components.)

Summarising, functions typically provide the customers view on the product. Additionally, they help engineering design departments to get an overview of the features a product needs to provide. This happens already at very early stages of the development process without having to know about the components that are going to be designed.

This paper uses the expression 'function' in a sense of 'technical function' that is describable solely by inputs, outputs and the transformation of energy, material and signals between them. Particularly, the solution (e.g. a physical component fulfilling that function) is not known at this stage (Rodenacker, 1970). Functions serve as a starting point to look for physical effects to generate principle solutions.

Other uses of the expression like economic or aesthetic functions in industrial design are not addressed here. Although engineering design methodology suggests the use of a strict and guided product development process including the formulation of product functions in theory, engineering design practice often does not make use of these already existing approaches. Several reasons for that are assembled by Franke (1999).

2.2 Existing Methods and Implementations

Functional views of products and the corresponding methods are well-published within the last decades. An overview is given in the following section.

Systems Engineering as introduced by Bell Laboratories in the early 1940s is an approach that is centred on the idea to integrate the functions desired by customers at the earliest possible point in the course of the product development phase (Chestnut, 1967). Until today this methodology is adapted by enterprises and a multitude of software tools exist. Most recently the comprehensive description language SysML gained importance.

In the seventies of last century, Nam Pyo Suh started working on his Axiomatic Design theory which he published beginning two decades later (Suh, 1990). His book describes a consistent methodology for the well-structured design of technical systems. It is entirely based on the transformation of predefined requirements into feasible solutions. Suh introduces four different domains, whose correlations are covered by matrices and mathematical operations. The second domain covers so called Functional Requirements which can be seen as functions in the understanding of this paper.

Koller introduces functions as a central part of product development processes (Koller, 1998). What makes his work special is that he elaborates on the fact of subdividing a so called overall function into subfunctions repeatedly each time by detailing their description. This procedure takes place until either a technical solution for a function is known or the function is not dividable. Those functions are entitled elementary functions. Koller provides possible solutions for them by supporting engineers with effect catalogues that offer physical effects directly associated with the elementary functions (Koller, 1998). Koller's methodology is laid out in detail in section 3 of this paper.

For Pahl and Beitz functions are a fundamental part of a structured engineering design process. In their book, they sum up different approaches from several authors: most notably the works of Rodenacker, who proposed generally valid functions for the use with binary logic (Rodenacker, 1970), Roth, who focusses on the general applicability of functions, (Roth, 2000) and Krumhauer, who concentrates on common functions with special consideration of the types of interrelationships between the functions, (Krumhauer, 1974), are to be mentioned. In the course of their book, Pahl and Beitz continue to rely on Krumhauer's definitions of functions and the according structures (Pahl et al., 2007).

Ehrlenspiel introduces a slightly altered definition of functions (Ehrlenspiel et al., 2007). In contrast to Koller and Pahl, he particularises, that working with functions primarily fulfils the task of intensively clarifying the purpose of the product to be developed before actually starting with the design of the product too early. He suggests focusing on the basic functions and elaborating a precise formulation of them by using a noun and a verb for each function. However, he argues, that in case this procedure turns out to be confusing and not leading to a better understanding of the task because of a large number of functions and complex interrelations between them, it is an appropriate approach to incorporate methods for synthesising function structures like suggested by Pahl or Koller into the engineering process (Koller, 1988; Pahl et al., 2007; Ehrlenspiel et al., 2007).

Besides that, many researchers covered functions in engineering design processes throughout the last decades. A methodology that does not necessarily rely on function structures but that can be used to overcome contradictions resulting from them is Altshuller's TRIZ (1979). Equivalent to the 'principles' of Pahl and Koller, Altshuller establishes the VePol which can be seen as a substance field. Catalogues of physical effects are applied similarly to their use within the Koller methodology.

Miles uses functional analysis to integrate economic aspects with customer desires and engineering design in the course of this value analysis and engineering (1972). An approach that uses the function concept as well is the function-behaviour-state model (FBS) of Umeda et al. (1990). It enhances the previously presented approaches. Although being based on the works of Rodenacker, it leaves the field of strict function formulation and subdivision into elementary functions (see above) needed for the application of design catalogues for physical effects.

A different aspect of the importance of functions becomes apparent when looking further along the product development process. It is vital for enterprises to rely on solid product architectures for their products. Ulrich establishes the so called product architecture, which is the mapping of functions to physical parts of a product (Ulrich, 1995). By creating their products with appropriate product architecture, enterprises have the ability to design products that can be changed covering new requirements from the market by adopting single functions and the related component. A comprehensive overview of product development methodologies and the use of the function concept in particular is given by Tomiyama (2009).

What is common with all presented methodologies and approaches is that they originate from a time where computer aided support in development processes was either not present at all or just in its infancy. Hence, it is possible to execute all methods with pencil and paper. On the one hand, this is an advantage as it shows how simple and clearly defined the methods are. On the other hand, a lot of potential is wasted as computerised approaches offer to leverage the complex relationships between the large amount of principle solutions in order to discover potentially innovative product ideas.

However, different projects started to implement the modelling of functions into software applications. This ranged from simple realisations of the conventional procedure with graphics applications to more ambitious approaches where additional aspects of complex function structures and the relations between functions are modelled. One example is the IDeFiX tool that Vietor introduced. It enables users to conceptualise multidimensional function structures with adaptive levels of detail for single subfunctions (Vietor et al., 2009).

Nevertheless, what is missing is a computer aided approach that helps to create innovative products by utilising the advantages of function synthesis and variation of different effects taken from catalogues.

3 KOLLER METHODOLOGY

This section gives an overview of the engineering design process that Koller presented, especially his definition of functions and function structures. Koller presents the overall aims of engineering design research as follows: (Koller, 1998)

- Conception of general (product neutral) and specific (product specific) design processes.
- Development of a tool to create qualitative und economically better products.
- Rationalisation and creation of prerequisites to automate engineering processes (CAD).
- Creation of means for better understanding and manageability of the permanently enlarging field of mechanical engineering knowledge.
- Achievement of an improved patent system.

One of his key aspects, that makes his publications stand out, is the clear focus on functions, function structures and principle solutions.

3.1 Using Koller's Methodology in the Product Development Process

The general procedure to develop products with the help of engineering design methods is similar within different approaches (Koller, 1998; Pahl et al., 2007; VDI, 2221). To obtain a consistent understanding of terms and definitions, an archetypal engineering process adapted from works by Pahl and Beitz, is taken as basis for explanations in this paper. They define the main steps with the search for a solution in mind (Pahl et al., 2007). The four basic steps are illustrated in Figure 1.

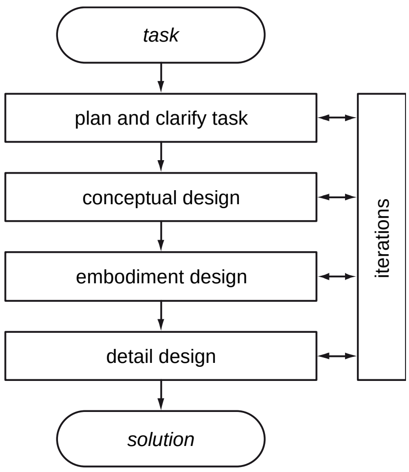

Figure 1. Main aspects of an engineering process (adapted from Pahl et al., 2007)

The first substep in ‘plan and clarify the task’ is to analyse the problem. The second step is to create a list of requirements. The ‘conceptual design’ phase includes the determination of the best possible solution. The next step–‘embodiment design’–deals with finding the rough design for the product. The final physical shape of a technical system is conceived in the phase of ‘detail design’. Koller’s catalogue is intended to be integrated in the ‘conceptual design’ phase. The corresponding methodology will be detailed in the next section.

3.2 Koller’s Approach of a Design Process

Technical Systems

All products can be considered ‘technical systems’. In addition to that, all products feature a purpose that can be to change or conduct energy, material or signal. Therefore, Koller classifies technical systems according to their main flow (energy, material or signals accordingly). (Koller, 1998)

Systems of ‘energy transformation’ can be classified in energy or energy converting components. These elementary functions are divided according to their function in change direction, in- or decrease, channel, insulate, divide, collect, separate or mix energy items. Technical systems which mainly transfer energy are called machines. Systems of ‘material transformation’ can be classified according to their application in change, in- or decrease, channel, insulate, join or loosen, divide, collect, separate or mix material ones. These are technical systems with the main purpose to convert material and/or enable the flow of material. They are called apparatuses. The ‘signal or data-transformation’ systems can be separated in connect, reproduce, recode channel/insulate or store items. These technical systems are called devices.

Function Structure

Mostly all these flows are involved in a technical system at the same time. Pahl and Beitz (2007) subdivide between overall functions and subfunctions. The overall function is equivalent to the purpose of product and covers all aspects while subfunctions consider smaller problems. The subfunctions together form the overall function and the result is the structure of the function. This itemisation of the overall function into subfunctions is exemplarily shown in Figure 2.

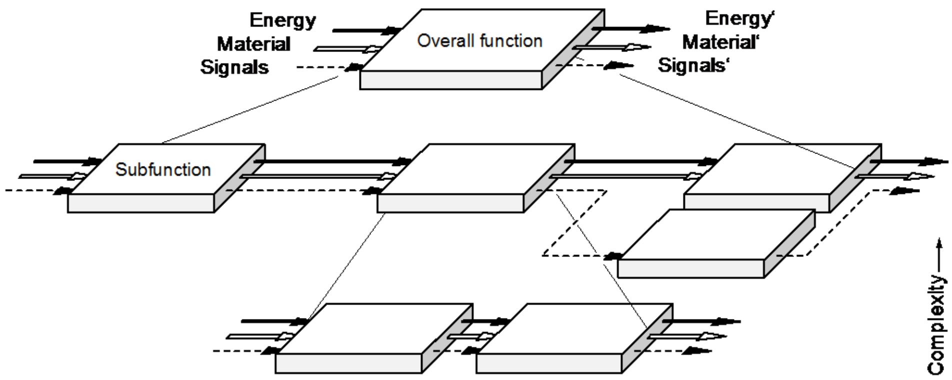

Figure 2. Generating Function Structure by breaking down the Overall Function into subfunctions (according to Pahl et al., 2007)

Elementary Functions

The Koller methodology enables systematic innovation by abstracting the purpose of product to requirements and functions. These have to be decomposed to elementary functions. It must be ensured, that the compiled elementary functions still fulfil the requirements and–as a whole–realise the product functionality. The main idea of Koller is to abstract all functions to elementary functions. For these, physical effects can be found. The main advantage of this procedure is the implementation of functions based on the use of physical effects. Subsequently the physical effects can be incorporated by principle solutions. However, the realisation of a function may need several physical effects or the realisation of a special function can be solved by different physical effects.

A catalogue with several physical effects was compiled by Koller who organised this catalogue by the types of flows. Figure 3 displays a subset of the elementary functions classified by their kind of flow. The benefit and core thought of Koller and the catalogue is that the engineer is more independent from his knowledge of physics and it is feasible to find new solutions by using previously unknown effects. By design, it is possible to find physical effects for every elementary function.

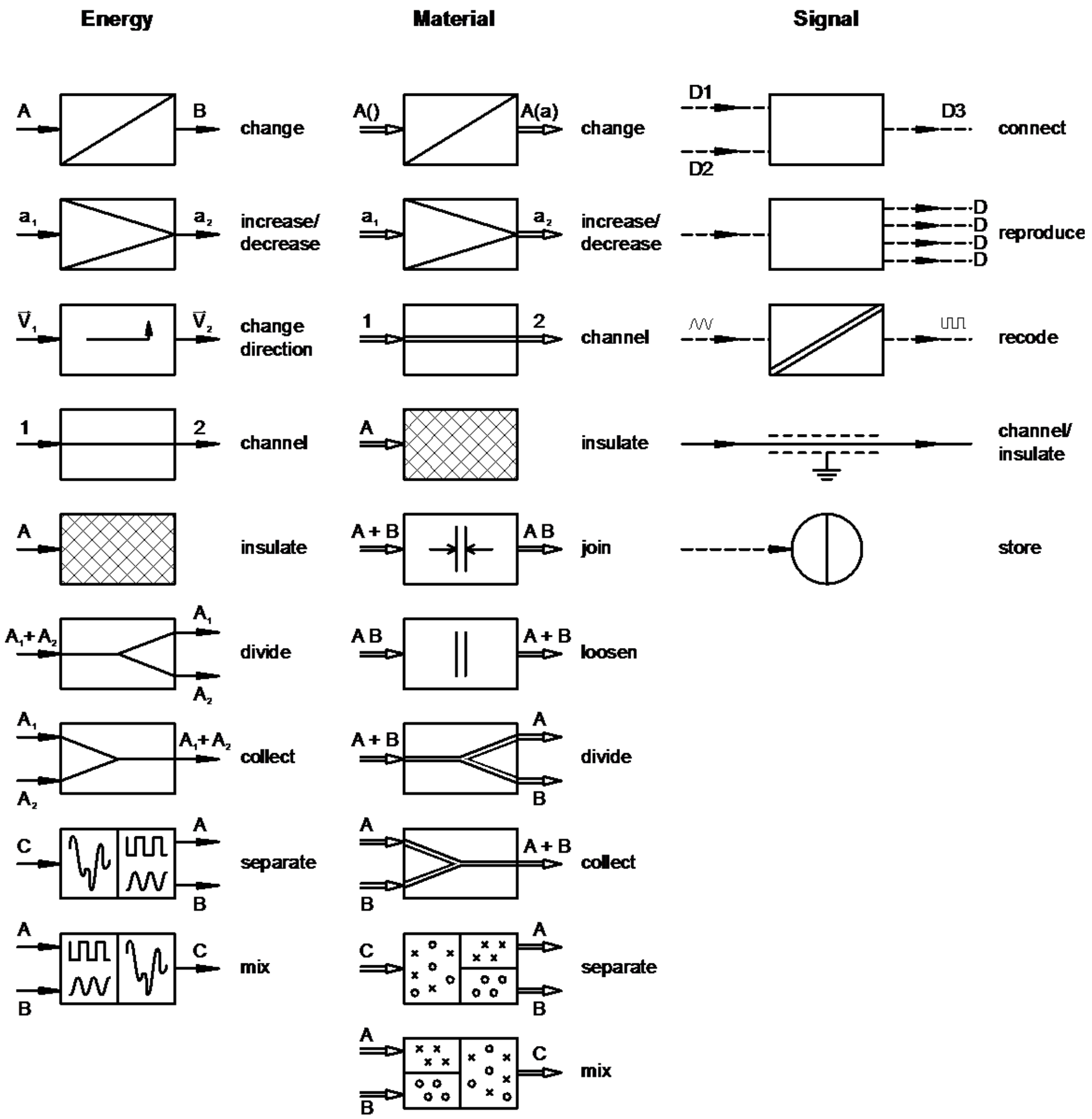

Figure 3. List of Elementary Functions classified by types of flow (according to Koller and Kastrup, 1998)

Effect Catalogues

In addition to Koller, Roth (2000) defines catalogues for engineering design as a useful pool of knowledge which is systematically presented as a table. These catalogues can be organised on physical effects, geometrical characteristics, material or manufacturing methods and standard or often used parts (VDI, 2222-2).

The starting point to apply the catalogue is the function structure. All subfunctions have to be defined as elementary functions. At this stage, the catalogue can be used as assistance to find the physical effects for every single elementary function being present in the function structure.

By varying physical effects for the subfunctions a field of solutions can be spanned. If it is possible to find every physical effect for an elementary function there will be a complete solution field.

Morphological Box

After finding physical effects for the realisation, these effects have to be synthesised to the principle solution (Koller, 1998).

The morphological box was first defined by Zwicky (1971). It is the systematic collection of all subfunctions and their feasible physical effects. A huge two-dimensional matrix is setup providing a row for every subfunction and an entry for every physical effect including a corresponding principle solution. According to Koller, the field of solutions now can be generated by combining entries from the morphological box (Koller and Kastrup, 1998).

4 COMPUTER-AIDED METHODOLOGY FOR A FUNCTION-BASED ENGINEERING DESIGN

4.1 Disadvantages of a paper-based approach

As shown in the chapters before, methodologies for product planning and product development, especially the Koller methodology, are strictly systematic. This is a benefit that qualifies them for the implementation within a computer application (Koller, 1998; VDI, 2221; Pahl et al., 2007).
Especially the Koller catalogue is difficult to use in paper-based version because of the vast amount of information. Therefore, it is complicated to use it without having a detailed overview of the catalogue. It is also impossible to use the method without knowledge about the concept and the right usage of the catalogue, two reasons why the method is currently not anticipated in the industrial environment.
One additional reason might be the overwhelming dimension of the created solution field. E.g. a simple product consists of 10 subfunctions. For every subfunction 5 physical effects with corresponding principle solution may be found. This results in a solution field of nearly 10 million possible combinations, which of course is not manageable in an enterprise environment.
To overcome that shortage, a computerised approach has been developed and continuously extended. First there is better user ergonomics and therefore a better acceptance of the method. Second there is a chance to optimise the conceptual quality. The benefit of support by computers is the chance to increase the variety of good solutions without losing the overview of the concepts because computers can handle large solution fields in a better way and present only relevant information to the user.

4.2 Implementation of computer aided Koller tool

In a first implementation, a software prototype was designed that offers the basic functionality of a digitised Koller catalogue (Müser, 2011). With the help of this tool, it is possible to create a model of the product's function structure within the computer by specifying all functions as well as their specific inputs and outputs. This kind of problem description is necessary to use Koller's catalogue, because the physical effects are sorted by their kind of flow and their elementary function. The current implementation realises a visualisation of the function structure in a first step. Figure 4 displays the main windows of the software prototype. A library of available elementary functions is listed on the left side of the application window. From there, single function blocks can be picked up and placed onto the main canvas. The software provides a simple user interface for connecting the function blocks with each other taking their specific kind of input and output flow into account. Every elementary function is a container for a transformation of input to output. However, at this point, it is strictly a solution-neutral description.
After having modelled the function structure, the next step is to find physical effects for every single elementary function. In order to create a high quality solution field for the actual product, it is necessary that the function structure describes it in a way as abstract as possible.

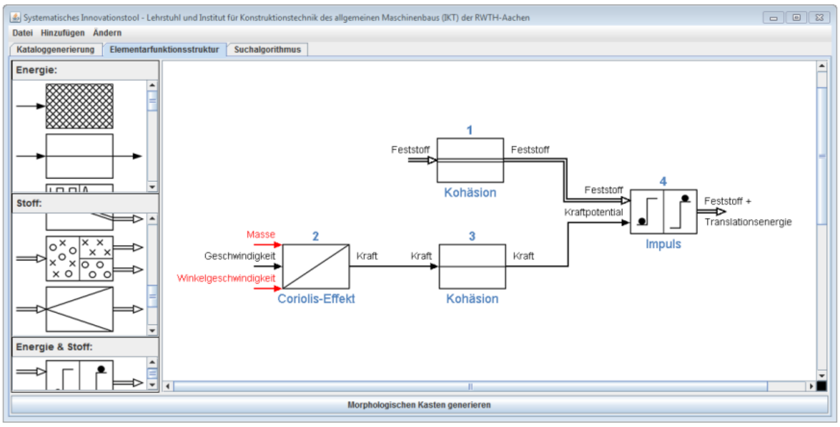

Figure 4. Computer aided conception of Function Structure

Finally, a morphological box can be generated, the matrix featuring all elementary functions of the function structure in the first column. For each row, all possible effects for one elementary function are listed. In a second step the possible solutions are listed in a morphologic box and the combination of the effects can be chosen. This alone would be a very time-intensive step when using Koller's method in conventional way with pencil and paper and the help of books that aggregate principle solutions and physical effects. However, this task can easily be performed by a computer. An exemplarily generated morphological box is displayed in Figure 5.

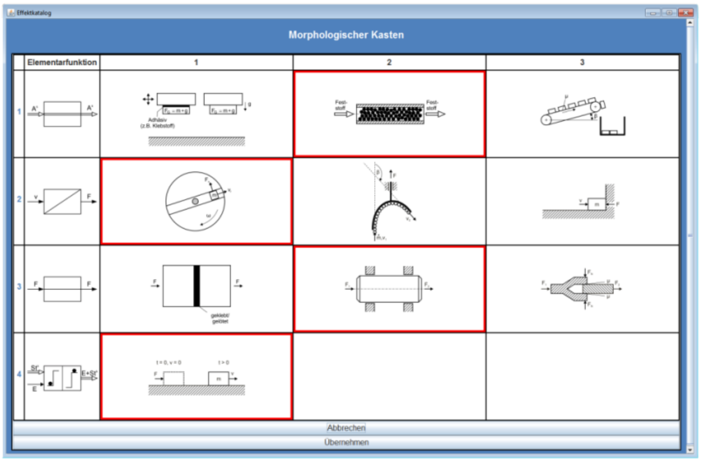

Figure 5. Computer aided automatic generation of Morphological Box

In addition to the simple assembling of the morphological box, extended information about the effects is established directly within in the software, so the user gets more information on a specific effect by clicking on it. This feature is a major improvement to the conventional way because not every engineer knows about all available physical effects. Hence, a knowledge database is integrated and can be easily extended by operators in order to integrate specific company knowledge. One advantage of this first implementation is to find at least one good combination of the effects by using the software. It is easy to increase the number of possible effects, but it is not easy to find high quality combinations because the user loses the overview very quickly. The problem of the combinatorial explosion is not solved, although it is easier to synthesise a solution field. To improve on this status, the software has been enhanced to manage the variety of solutions.

4.3 Enhanced computer aided Koller tool

The initial prototype concept has been revised and extended within a second project. The aim was to reduce the quantity of combinations to increase not just the number but the quality of the tool's output. (Apfel, 2012) To limit the numbers of combinations in the solutions field, a promising approach is to use magnitudes for the effects, so the combination of two effects featuring different magnitudes on the same kind of flow is not possible. Hence the variety is reduced. This approach has been successfully implemented and validated with implicitly integrated magnitudes for most of the physical effects.

Another approach is to manage the combination rules with respect to the kind and quantity of the effective geometry areas, incorporating the contact and channel model concept of Matthiesen (2002). The model is mostly used for analysing and conceiving the geometry of any technical shape. However, it turned out to be difficult to implement it for choosing effects for a concept.

The possibility to reduce the complexity by reducing the numbers of displayed combinations on the one side sacrifices the chance to generate originally new ideas and thus innovations which have not been thought of when creating the software. For instance, it can become possible to use a physical effect in new magnitudes that were not initially implemented.

4.4 User-oriented software tool

As both improvements did provide solution fields of higher quality than the paper-only approach but still left room for even better support, a third approach is being implemented that intends to accompany the combination choice by the operators' personal know-how. It has been the aim to enhance the tool in a way that it supports an experienced engineer to create new ideas. He has the knowledge about possibility and feasibility and especially the knowledge about the own company. If he does not have the knowledge, he is at least in a position to obtain it. A chance to get a benefit by the tool is to ask the engineer "Is this effect possible in *your* new product?" However, agglomerating all this knowledge into a software tool with an attached database might not be the best way to get a universally applicable tool with a reasonable size. Thus, the improved concept is to involve the expert in the decision process actively by asking him the right questions and giving him the necessary, profound information for the decision in a guided way.

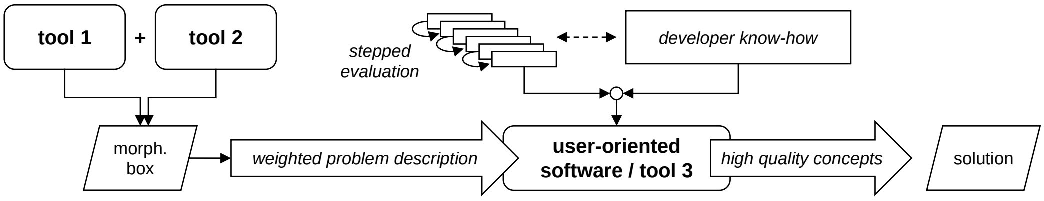

Figure 6. Software concept

The new tool features the possibility to weight the input in order to highlight the important product functions. In case of a product redesign or a patent avoidance always product features exist which are more important than others. The main idea of the software's concept is visualised in Figure 6.
For the graphic user interface a concept analogous to that of a car configurator has been chosen. Altered from that is the actual matter of decision. Not the components of the car get evaluated one after another but the different product functions with their automatically associated (with the help of existing software modules as presented above) physical effects and principle solutions. Same is the task for the operator: The objective is to find one configuration out of all possible ones. This one may not be the best configuration but it is a subjectively best version of the car (or the product concept respectively). Often requirements of the new product are implicit and often they are not described and communicated accurately. But mostly the product developer has internalised them to include them in his decision. So one way of finding a good combination of effects is a stepped decision, like it is done by car configurators where not all possible combinations to choose from are displayed to him at the same time. He rather decides over every product aspect in a guided, stepped process. However, one risk is to neglect interactions between the effects. This implementation has been tested in education and showed significant improvements over the old approach as operators where not overwhelmed by the multitude of possible solutions in the morphological box.

5 OUTLOOK AND CONCLUSION

The topic presented is undergoing current research at RWTH Aachen University. One future difficulty is to render the methodology usable for industrial use in addition to the use in educational surroundings. Therefore, making combinatorial explosion manageable by using extensive digitised catalogues of effects has the highest priority. Future steps for realisation will be the implementation of a new functionality to integrate evaluating methods for the effects and their combination to get a better overview about concept decisions. Moreover, a process for the proper use of the tool in industrial environments is being developed. In line with that, the validation of the efficacy of the third iteration of the Koller software tool in non-academic environments is scheduled.
Concluding, the presented method and the tool provide a convenient way to systematically conceive innovative product concepts (effectiveness) in considerably shorter expenditures of time (efficiency).

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