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An Approach to Model-based Parametric Design of Mechatronic Systems

Peter Hehenberger[1]

[1] Johannes Kepler University Linz, peter.hehenberger@jku.at

ABSTRACT

The market's demand for ever shorter product life cycles and the resulting reduction in product development time present new challenges to the product development process. Considering traditional approaches to the development and design of technical systems, the design process has changed considerably in recent years, in particular due to more extensive use of computer programs and their increasing efficiency. This requires that the design engineers re-orientate themselves, since the procedure is entirely different from the earlier approach. Furthermore, in the mechatronic system development process, not only are the geometrical design parameters themselves interdependent, they also depend on the design parameters of the various disciplines involved.

Keywords: product model, parametric design, mechatronic systems.

1. INTRODUCTION

In today's industrial plant design sector, as in all other industries, cost and time pressure are steadily increasing. The reasons are the general acceleration of economic processes and the resulting price pressure due to globalization. Diverging customer requirements often make it impossible to standardize whole plants [1, 4]. Standardization is therefore applicable only to machines or at the component level. A high number of new product developments (unique pieces) increases not only the risk of error, but also development time and staff requirements for the plant builder. At the same time, the market requires a significant amount of variation within a period of five years. The changes in economic growth along with the different periods in the product life cycle result in fluctuations in demand. A plant builder can react to such fluctuations by enlisting the support of engineering partners and leasing personal during peak periods or by reducing permanent staff during weak market periods. The latter, however, leads inevitably to large know-how losses and higher training costs. The development of unique products differs from the design of serial products in that its development process is limited by the shorter project completion time given. Several processes need to overlap or run simultaneously. Moreover, the cost-saving potential of optimization is significantly smaller because of the lower quantity produced. All these factors increase the need for tools that improve efficiency in product development. Most companies embrace the advantages of 3D CAD. Some add different PLM systems [11] to support development and production. Standardization with advantages such as consistent quality and low price is also applied increasingly often in industrial plant construction.

The benefits of standardization are greatest if the company owns the required manufacturing facilities or at least has fixed manufacturing partners. However, this is usually not the case, because owning such facilities is usually only economical for the production of core components and entails the disadvantage of limited flexibility. Furthermore, the acceptance of standard products is generally rather low as, among other reasons, customers want to integrate their experience into the development.

Another approach to reducing the costs and execution time of a project without losing flexibility is to use parametric models. In contrast to standardization, the cost reduction due to parameterization is significant even for low product quantities. To minimize costs, the plant manufacturer must solve the problem of finding a balance between standardization and parameterization, considering the boundary conditions and the strategy of the company.

2. BACKGROUND

The market's demand for ever shorter product life cycles and the resulting reduction in product development time pose new challenges to the product development process. Especially in today's

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economic environment with global competition and high dynamics, a superior design concept is crucial for a product, as it largely determines its success. For any new product, the question of how it can be realized is less important than how a promising superior product concept can be found. In the traditional linear model of design, the process flows from synthesis to analysis and evaluation. Design methodology at the conceptual level includes, as a goal, the creation of innovative concepts, comprising a description with little detail but with sufficient relevance for evaluating their essential properties in comparison to other concepts. The main properties (e.g., parameters, costs) of the product are fixed during the conceptual design phase of the product development process.

Considering traditional approaches to the development and design of technical systems (e.g., VDI guidelines, VDI 2221 [12]), the design process has changed significantly in recent years, particularly due to more extensive use of software tools and their increasing efficiency. This requires design engineers to re-orientate themselves, since the procedure is entirely different from the non-parametric approach. Design engineers must familiarize themselves with parameterization before starting work on a suitable concept (design rules) for dependence. Defining new variants can produce entirely unwanted results later in the process if the parametrics are not properly developed.

A central question is therefore what degree of model parameterization is meaningful. It is conceivable, that parameterization is stopped at a certain point (i.e., degree of detailing) in the development process and fixed values are then used, since parameterizing a system completely to the last detail is costly. This transition from a parametric description of the model to one that selects from fixed components (modules) represents an opportunity to adapt expenditure and tailor a development task to the requirements. If this transition happens too early, modifying the model to accommodate later changes becomes very difficult. Clearly, the functionality –and thus also the complexity – of technical products increases if several mechatronic disciplines are involved [8].

Product models are an essential basis for handling and computer support of the development process: copies and variants can be generated more rapidly, and design modification becomes simpler. This does not only require more extensive use of computer-aided systems, but also their integration in order to enable loss-free data exchange, avoid sources of error and accelerate optimization cycles. The model description must ensure that gradual development of the integrated product model from abstract to concrete specification is possible.

The documentation of the results of each development stage becomes the basis for subsequent design steps. Both these results and other data, such as requirements, can serve as development directives or parameters for downstream development steps. Not only must the design methods be evaluated in terms of time and costs saved – quality assurance also plays an essential role in the development process. Important criteria are comprehensibility of the method for solution identification, provision of decision criteria, standardized operational execution of the development process, definition of criteria and characteristics for the individual giving full details and step question.

This contribution deals with the central issues of classification and simplest possible description and documentation of parametric design models, because 3D CAD systems and computer integration are not currently being exploited to their full potential. Furthermore, in the mechatronic system development process, not only are the geometrical design parameters themselves interdependent, they also depend on the design parameters of the various disciplines involved. [2, 10].

3. MODEL-BASED PARAMETRIC DESIGN

The structure of the product model aims to incorporate product information from the entire product lifecycle. This requires a structure that can already be used in the early phases and does not change throughout the product development process. Normally, product information is structured according to the geometry of the product or according to the assembly structure of the product. This results in problems in the early phases of the product life cycle, because the geometry or assembly structure is an outcome of the development process and neither exists in the early phases nor is stable during the development process [3, 10]. Monedero [15] gives in overview about techniques in parametric design. This includes variants programming by macros or procedural modeling and also history-based constraint modelers. Parametric models are very important tools for complex activities such as engineering design. The preliminary design phase is often characterized by cascading series of what-if questions. Some of these questions reflecting requirements may be of controversial character from their nature, and are related to complex dependencies between shape, topological structure, strength, performance, physical behavior etc.

The "object" which is most stable during product development is the set of resulting properties, which defines the product. As previously stated, requirements can change over time, but, strictly speaking, changes in requirements should result in the development of a new product. Trying to find a product information structure which is suitable for every set of requirements ultimately results in a structure that is identical for every product development process [6, 7]. Note that a definable property is not equivalent to a geometric parameter. A definable property can be any property the designer defines directly (e.g., materials, manufacturing parameters, geometry). The totality of all definable properties defines the complete product with all its properties and its behaviors.

The resulting properties are used to structure the generally high number of definable properties. This is done by assigning each definable property to the resulting properties that were influenced by this definable property. As mentioned before, it is possible that a definable property influences more than one resulting property (for example, the definable property "material" influences the resulting properties "maximum weight" and "maximum stress"). A second level of structuring is achieved by assigning the definable properties to the different views. Each definable property can appear in a single view or in multiple views (for example, the definable property "material" appears in the view "producibility" and "costs"). In order to classify the definable properties in the matrix, meta-information (a tag) can be assigned to each of them. This meta-information can be the view or the product property influenced by the definable property. The relevant parameters and independencies can be also description by using STEP, as [14] will show.

3.1. Types of Assemblies and Components

Before starting the classification, it is necessary to establish a classification system that allows parts or assemblies to be distinguished with regard to the degree of standardization. Based on this classification, the modules and interfaces (control parameters) can be allocated when the concept of the model is formulated. Regarding the degree of standardization, three classes can be defined,

(1) the first of which includes the "customized components" which are not standardized and offer maximum flexibility in terms of design. We, however, want to focus on the other two classes, which have a higher level of standardization.

(2) The second class - "Parametric assemblies" – contains components with at least one feature with continuously variable position and size depending on certain parameters. Parameterized assemblies (components) include:

- one or more independent parameters with continuous ranges of values;
- one parametric 3D model and one manufacturing drawing that must be updated and checked whenever the parameters are changed.

(3) The third class – "Standardized assemblies or components" – can be divided into discrete-parametric assemblies or components (series), non-similar series and identical assemblies or components (see Fig. 1).

- Discrete-parametric assemblies evolve from parametric 3D models by discretizing the range of values of independent parameters. Their properties are similar geometry, the ability to be scaled by at least one or more independent parameters with discrete ranges of values in predefined increments. It is one parametric 3D model and one manufacturing drawing, which both require updating whenever parameters change. A good example is a roll chock with variable size depending on standard sizes of bearings in predefined increments.
- Non-similar series consist of assemblies (components) with, for instance, greater size differences and thus different geometries and a finite number of "3D models" and manufacturing drawings that should not be changed but only replaced. An example is the main body of a hydraulic cylinder, where the size of the pipe connection does not simply scale, but alters the design.
- An identical assembly or component remains unchanged in its shape and size, regardless of the application and the size of the surrounding parts, making it the "standard part". Such assemblies (components) consist of a "3D base model" and a manufacturing drawing. A good example is an inductive proximity switch

3.2. Mechatronic Product Development Process

The product development process using parametric models can be divided into three phases: project definition (concept, basic design), module design (detail design) and system integration [12]. In the first phase, after establishing a rough concept for the solution, the parameterization concept can be chosen and the control parameters of the product with their possible ranges of values can be initially determined. This forms the basis for creating the module structure and interfaces. At this point, assemblies with known components can be classified, followed by the rough design of the control assembly and the main assembly. The second phase consists of the detail design of the modules, including optimization and standardization using parametrical adjustments. The third phase includes functional testing of the model, any property-ensuring measures, such as stress analysis and collision analysis, and the resulting adaptations (Fig. 2).

3.3. Classification Method

For reasonable allocation of modules (components) to the defined classification system, aspects such as manufacturing, engineering, delivery time, execution time, quality and customer satisfaction must be considered. As previously mentioned, the ultimate goal of parameterization and standardization is a direct or indirect reduction of costs while retaining quality. Of course, the return of investments has to be positive. To ensure this, the potential for reducing

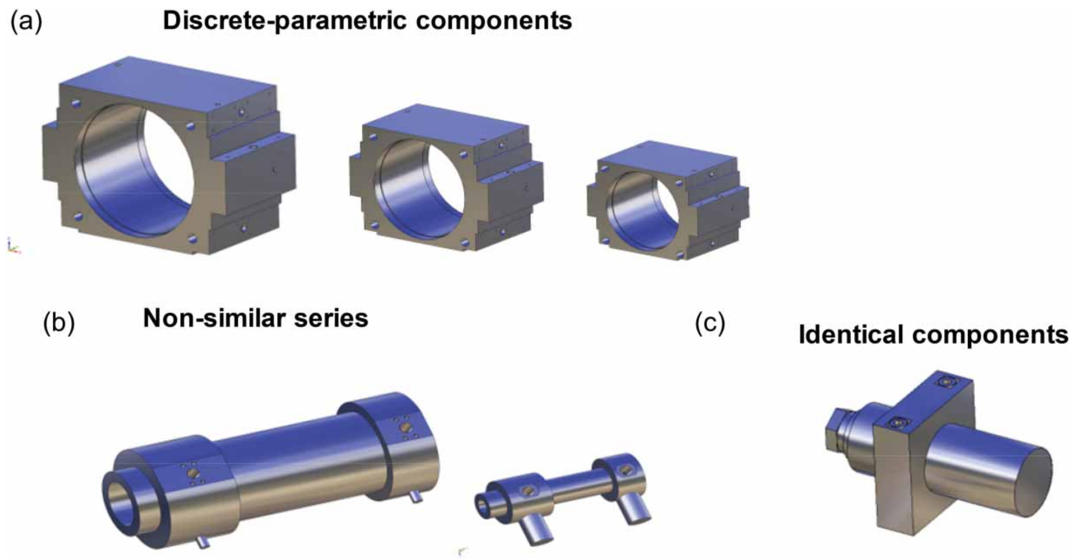

Fig. 1: Standardized assemblies or components.

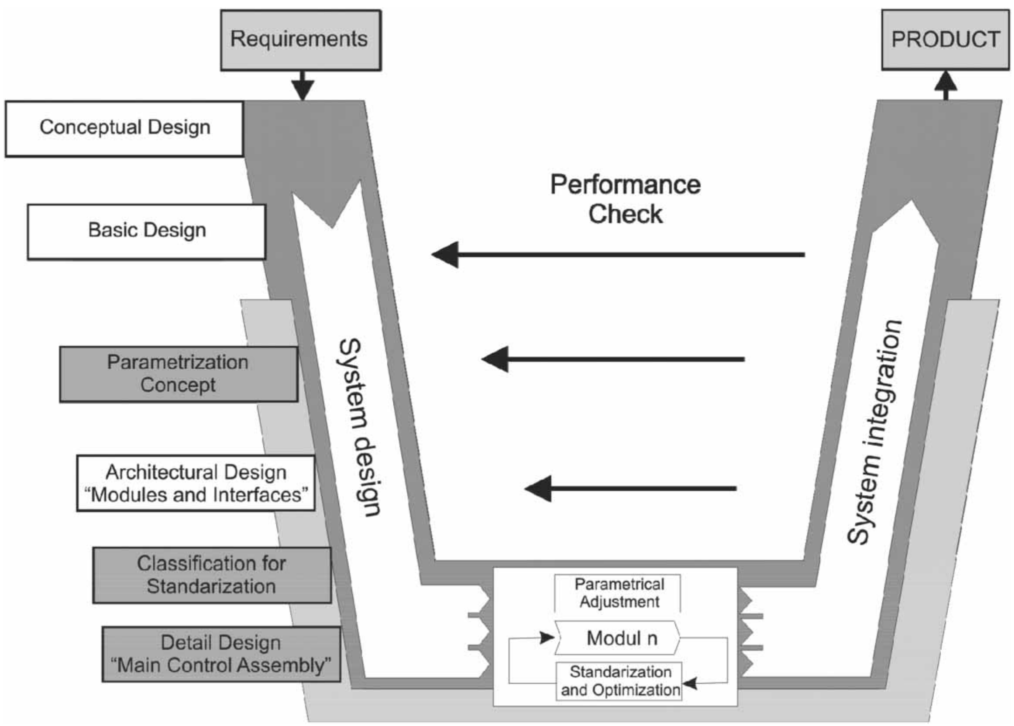

Fig. 2: Proposed approach.

costs and the expense for the improvement must initially be estimated and then compared. The parts can then be classified using the flow chart shown in Fig. 3.

The first step is to determine the dependency of the current component on the current parameter in the predefined value range. If the dependency is not given or is so small that it can be neglected, the component can be preliminary classified as identical with the current parameter. The next question is whether standardization is possible. If not, the component can be classified as "customized". However, if it is possible, the question arises of whether defining the component as "identical" with the current parameter is possible and profitable. In case it is not, the question remains of whether it is possible to perform the function in the given space with a similar but scaled geometry. In this case, it is again only a question of profitability whether a discrete ("similar") or a continuous ("parametric") scaling is to be used. The

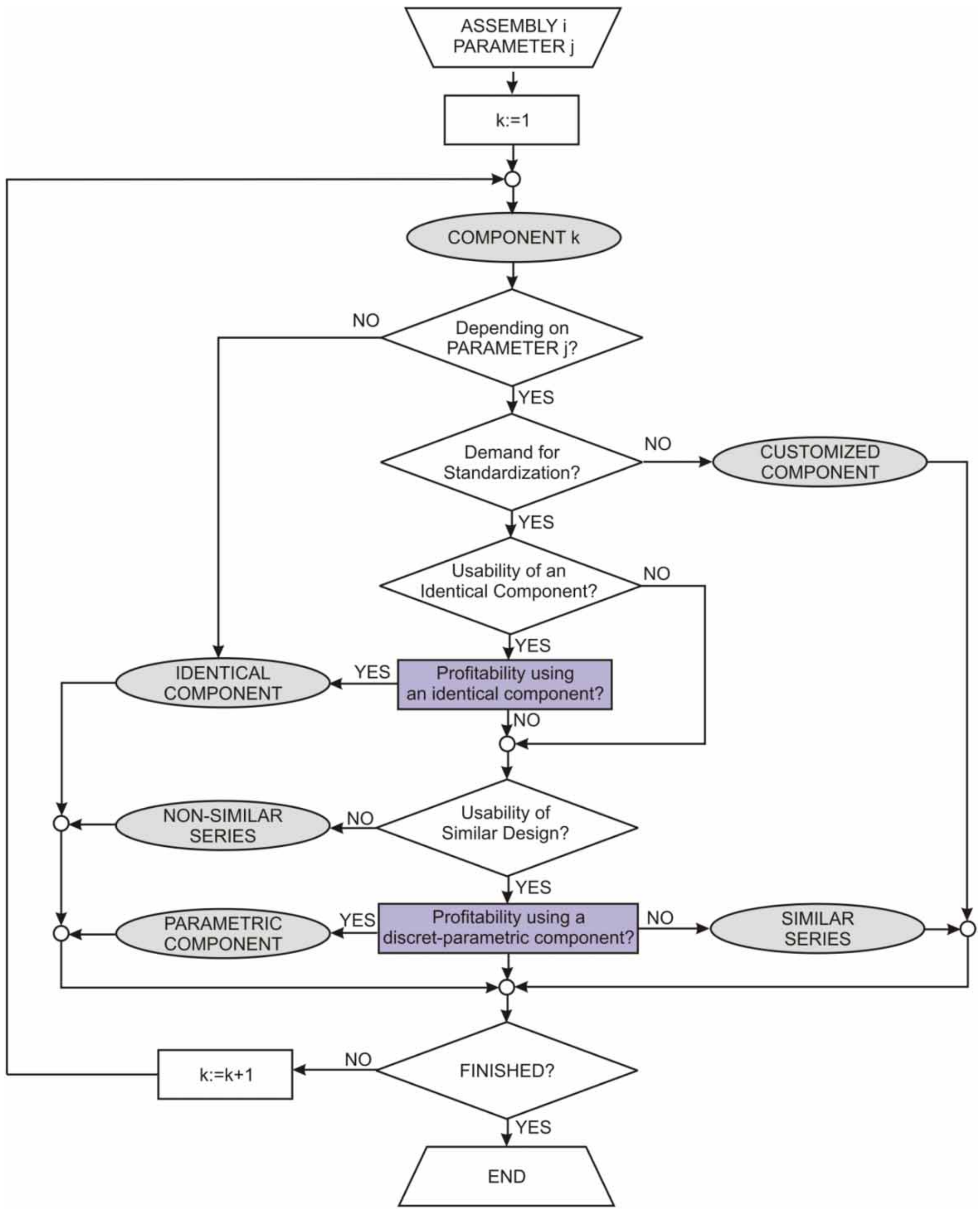

Fig. 3: Classification method.

following factors are relevant to determining the profitability of using identical components: costs, delivery time of manufactured parts, execution time and risk.

To estimate the overall costs, the production costs and engineering costs must be considered separately. On the one hand, the use of different sizes for different loads has a positive effect on manufacturing costs, since the components can be optimally used. On the other hand, standardization increases the quantity, which can also potentially reduce manufacturing costs. The use of identical components usually has an effect on the surrounding components. Therefore, not only the component's effect on production costs but also that of its environment must be investigated and considered. Possible cost savings by using different sizes must be weighed against the increased engineering effort required for development and maintenance of serial products. To this end, the boundary conditions of the company must be carefully investigated and considered.

3.4. Parameterization

The use of standardized and parametric components makes the implementation of CAD models very complex; therefore, the choice of CAD system and

Evaluation criteria	CAD-internal	CAD-external	Hybrid
Number of parameters on the interfaces to the external program	small	large	medium
Number of required parameters and relationships	small	large	medium
Simplicity of operation	good	bad	medium
Overview	good	bad	medium
Documentation effort	small	medium	small
Calculation capabilities	small	large	large
Algorithmic loops	no	yes	yes
Logical operations	rather no	yes	yes
Table handling	bad	good	good
Automated assembly configuration	no	medium	medium
Information content in the model	high	low	medium
Effort to change the CAD program	high	low	medium
Utilization of the functionality of the CAD program	high	low	optimal

Fig. 4: Differences between CAD-internal, CAD-external and hybrid parameterization [9].

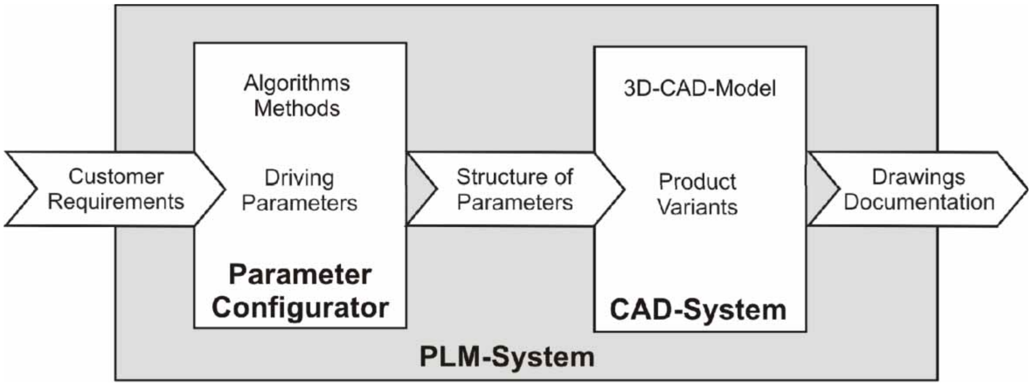

Fig. 5: Method for parametric modelling.

implementation concept are very important. In general, there are two possible ways to create parametric 3D CAD models. One way (internal parameterization) is to use a CAD system with sufficiently extensive functionalities for parameterization. The other (external parameterization) uses a CAD system with more limited functionalities and an additional calculation program which processes all parameterization tasks. This "hybrid parameterization" seeks to combine the advantages of internal and external parameterization and to eliminate, as far as possible, the disadvantages. The goal is to split the tasks of calculation program and CAD software such that the functionality and capabilities of both programs are fully utilized (see Fig. 4).

The benefits that result from such a mixed form of the parameterization are obvious:

- Optimal utilization of the capabilities of the CAD program results;
- simpler parameterization and easier operation;
- full use of the advantages of an external and an internal parameterization and reduction of the disadvantages;
- reduction of interface parameters – only parameters directly resulting from technological and stress calculations are used; most of the parameters remain in the CAD program;
- fewer positioning and guiding parameters;
- model functionality is given without the use of excel sheets, because the parameters can be directly entered into the model manually;
- easy replacement of modules;
- changing the CAD program is easier than with purely internal parameterization;
- the modular design simplifies the use of variants and custom and optional assemblies.

Nevertheless, some disadvantages remain:

- Part of the know-how is in the model and is thus less well protected (in the case of collaboration

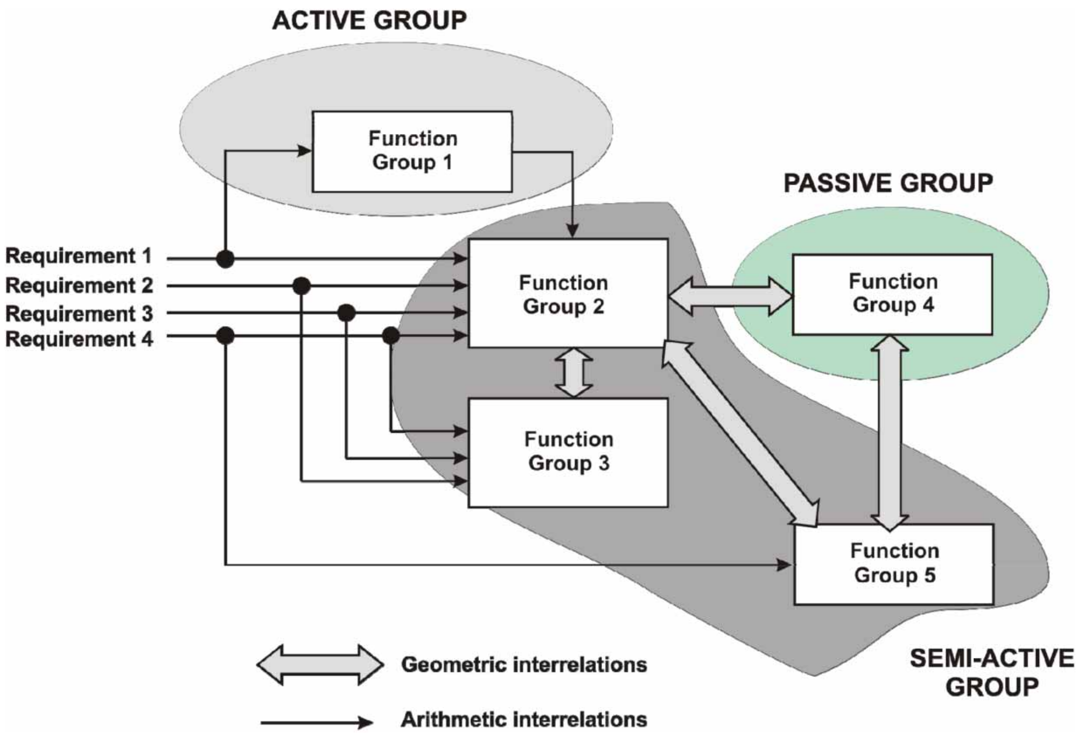

Fig. 6: Relations between requirements and function groups.

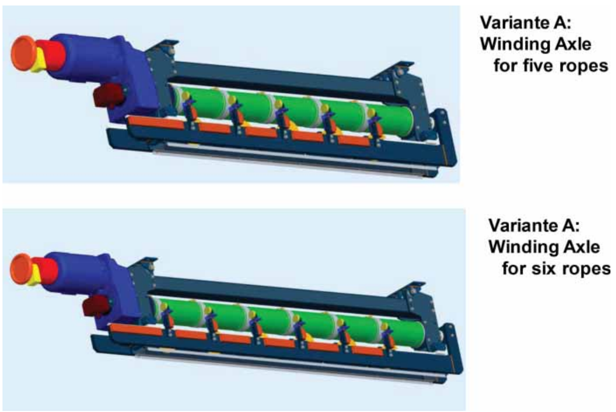

Fig. 7: Two variants of the driving axle.

with external engineering partners) than in the purely external parameterization.

- Modeling requires more consideration of the specific features of the CAD software.

4. CASE STUDY

The task of the case study was to parameterize a grid winch system called "Driving Axle" and to build an automatic product configurator for different customer requirements in order to improve development efficiency [5, 13].

Because of the numerous parameters and their relationships, parameterization of many modern products, particularly of complex mechatronic systems, is difficult to accomplish. Therefore, we developed a suitable parameterization concept: First, the entire system is divided into groups according to a function-based analysis. After analyzing the internal and external relations, the groups are defined as "active", "semi-active" or "passive". This characterization significantly facilitates determining and defining a suitable parameter structure and sequence of parameterization. It is considered to be one of the best solutions for implementing parameterized modeling in small and midsize companies.

Figure 5 illustrates an approach to the hierarchical decomposition of the design parameters according to the customer requirements given. Further, the computer-aided realization in the different software tools used in the design process is shown. Interactions occur between our parametric configurator, 3D CAD systems and PLM systems.

The relations between customer requirements and functional groups of the system can be classified as direct and indirect dependencies, which are described by arithmetic and geometric formulas. Fig. 6 shows these interactions in more detail for the case study "Driving Axle".

An arithmetic relation is a unidirectional relation, because we have defined inputs and outputs. Geometric relations are bidirectional, because they consider the interaction between two parts. The "sequence" of parameterization is very important. Based on the relations, three types of functional groups are defined: active, semi-active and passive groups. Combining the general requirements of software engineering and the specific requirements of this project, the configurator was realized using Microsoft Excel + VBA®. Compared to other implementations such as API programming, it is much easier to understand and adjust. Project cost and duration are accordingly reduced. With the information generated by the automatic configurator, the basic parametric model established in the 3D CAD tool is updated to obtain the new product variant. Fig. 7 shows two parametric variants of the winding axle (with the function group drive engine).

5. CONCLUSION

In this contribution, we have presented an approach to model-based parametric design of mechatronic systems. Our approach has two important advantages: First, a variety of system structures can be established and evaluated, and second a hierarchy of model parameters can be defined. Hierarchical models are essential tools in handling the increased complexity of such integrated design tasks. As the levels of detail specified during the design process increase, the models become increasingly detailed, resulting in a hierarchy of models and the parameters that describe them. We are confident that this point in particular plays a major role in the success of mechatronic products on the market.

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