MBSE-INTEGRATED PARAMETRIC WORKING SURFACES AS PART OF A PLM DESIGN APPROACH

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ABSTRACT

This paper demonstrates a concept for a cross-domain strategy for the sustainable processing and dissemination of product information. Important functional product features are explicitly mapped as working surface information in different domain tools with the help of the contact channel method and are integrated using a model-based systems development approach. The approach uses established state of the art design tools and can be integrated into existing product development processes, knowledge based engineering concepts and product (system) lifecycle management strategies.

Keywords: Product modelling / models, Product Lifecycle Management (PLM), Systems Engineering (SE), MBSE

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1 INTRODUCTION

One major challenge for product designers during the early phase of engineering design is to find an initial component shape. Usually, there is the possibility of an analogy consideration, revision or adaptation of an existing shape geometry in terms of variant design or adaptable design. But when it comes to a completely new design task, the developer must independently establish a geometric shape. Here, the use of knowledge catalogues can help to find a design based on reliable facts and findings. However, it is necessary to integrate such knowledge into the digitized development process. In respect of today's concurrent engineering tasks, this has to be done in a way that a consistent transfer of information beyond one's own development domain is ensured. Alternative solutions and operative decisions must be documented in a comprehensible way, too. The approach of virtual product design offers promising approaches in this respect.
Unfortunately, in today's product development practice there is no pragmatic, model-based system development procedure for a knowledge-based shape design of mechanical components existing, yet. Therefore, a need for action in the form of a method development for systemic development processes across the involved tools is indicated.

2 STATE OF THE ART

The approach presented in chapter 3 is based on today's state of the art engineering tools including knowledge-based engineering approaches in a 3D-CAD-System, model-based systems engineering and the use of product data management systems. Therefore, short resumes of the state of the art of the mentioned tools are given in the following subchapters. The presented research can be classified as a type 2 design research project according to the design research methodology by Chakrabarti and Blessing (Blessing, 2009, pp. 18 et seqq.).

2.1 Model-Based systems engineering

Technology evolution in the sector of information technology and the increasing complexity of mechatronic and cyberphysical product concepts in recent years have led to an increased influence of impulses from the fields of systems engineering and computer science on virtual product development (Friedenthal *et al.*, 2012, pp. 15 et seqq.). In particular, the development and dissemination of the so-called systems modelling language (short: "SysML"), which is based on the unified modelling language 2.0 (short: "UML"), has been established for the engineering of specifications, design and documentation of technical systems (OMG, 2017, pp. 3). With the help of SysML-based software tools with graphical user interfaces (so-called "modellers"), complex systems can be developed, managed, optimized, documented and visualized using a relational database. The system model generated in this way contains, for example, product use-case scenarios, a requirements database, the functional product structure, the physical product structure and physical or logical procedures and processes. In addition, cross-links between individual SysML elements can be used to map indirect interrelationships within the system model (e.g. linking of user requirements and physical parts).
In the field of systems engineering research, specific methodical procedures for the generation of SysML-based product and process models and their further use in the design process were developed (Lamm *et al.*, 2010, pp. 116 et seqq.).
In the context of the shape design of mechanical parts and assemblies, the FAS4M approach developed by Lamm and Weilkiens (FAS4M = "Functional Architectures of Systems for Mechanical Engineers") can be mentioned exemplary (OOSE 2016, pp.10 et seqq.). Using an extended SysML language specification (so-called "MechML") and closed-source interface programming, the authors demonstrated a dynamic coupling between a specific modelling tool and a specific 3D-CAD-system.
The topic of system modelling or model-based development using the SysML language is also referred to as model-based virtual product development (MVPE).
Recently, there have been increasing efforts to extend the MBSE approach to the CAx tools of virtual product development and to link domain-specific authoring tools (e.g. for calculations, simulations, etc.) with a higher-level system model using data technology (Blumör et al., 2017, pp. 196 et seqq.).

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2.2 Knowledge based engineering in 3D-CAD

With the aid of the existing software tools, synergy effects are used in modern product development processes (PDP) with regard to the workload and location-distributed, parallelized work through the method of integrated knowledge-based engineering (Pahl and Beitz, 2007, pp. 539). In terms of a modular product development, so-called product features can be handled as modular part elements of a product (Pahl and Beitz, 2007, pp. 181 et seqq.). Those features represent pre-designed partial solutions with known geometry and associated metadata (e.g. material, costs, delivery times, etc.). According to Feldhusen, the knowledge incorporated can include company knowledge, development and design knowledge as well as production knowledge (Pahl and Beitz, 2007, pp. 140 et seqq.). Today's 3D CAD systems offer the possibility of generating user specific knowledge elements (so-called "user defined features", short: UDF) in program-specific databases (Ugarte 2013, pp. 459 et seq.). Furthermore, models of the products of component manufacturers can be integrated on the basis of the exchange data formats already described via so-called service portals or external libraries (TraceParts, 2018 / CADENAS, 2018). The product features are applied or integrated into the product structure via geometric references (e.g. coordinate systems, points, axes, planes), the sum of which is also referred to as a skeleton file (Jianbin, 2018, pp. 22). Skeleton modelling can also be used in concurrent engineering to enable parallel development of assemblies and components of the same product.
In addition to component design, integrated knowledge management of today's 3D CAD systems can also be used to perform component or assembly testing (Siemens PLM, 2018). With the aid of the geometry and meta data information within the integrated databases of the 3D CAD systems, requirement checks, weight and center of gravity analyses or other user-specific test queries can be generated.

2.3 Product data management systems

Product Data Management Systems (PDMS) are software tools for product data managing, associated meta information and structural data management as well as the organization of change processes (VDI 2219, 2016, pp.6). Today, PDMS provide a comprehensive management approach for the integration of data and processes into the lifecycle aspect of product design by integrating different CAx tools into one database and transfer informations to ERP systems (VDI 2219, 2016, pp. 9 et seq.). Another important functionality of PDMS are cross-sectional data operations in the development process, such as administration and versioning of the product structure, simulation data management or long-term archiving of company knowledge (cf.ibid.).
It becomes clear that the use of a PDM system can have a multi-faceted operational character depending on the complexity of the product structure and the company's organization structure. PDMS in interaction with 3D CAD tools has evolved to an industry standard in development projects of medium-sized to large companies nowadays.

3 APPROACH

The procedure described in this paper explicitly addresses the new design of a mechanical component in a higher-level assembly group of a product development. Although most current product development projects represent modification, fitting or variant designs from a global point of view, the process of initial design finding is, in the author's opinion, almost always can be found in the form of a newly defined mechanical component within an assembly or an assembly group at a low product structure level (e.g. brackets, lever actuators, wheel carriers, frame parts). Despite their limited complexity, these components perform important interface functions within the product structure. Due to the increasing cost pressure and the possibilities of today's manufacturing technology (e.g. generative manufacturing), these components are often designed as integral components in which the final shape does not easily allow conclusions to be drawn about the underlying functional tasks.
In the context of today's global, site-distributed development and manufacturing of such components, a very high level of communication effort is currently required for the mutual coordination of all participants with regard to the function-critical geometric elements. In addition, such components are optimized in multi-cyclical, iterative development steps and, if necessary, adapted to given production strategies. This means that there is a risk that function-relevant geometry interfaces or topologies will not be considered at all or will be considered too late. This results in further change processes. In order to improve this situation, this paper proposes a knowledge-based method for finding the shape of such components using feature technology in the 3D CAD system and consistent data generation and transfer.

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An elementary part of the procedure is to support the developer in creating the rough shape of the product and at the same time to achieve a cross-tool mapping of the information gradually created. The designer is to be supported in the creative problem-solving process and relieved by the partial automation of complicated or time-consuming data processing steps. Depending on the conditions of the tool landscape used in a company, data can be transferred directly between the individual software interfaces or referenced to program-specific data by a connecting instance.

3.1 Concept

The overriding strategy of the approach described here is to generate digital data throughout the entire product development process. The focus is on the initial design of a single mechanical component, i.e. the transformation of a functional description into a virtual geometric shape in the early phases of product development. The procedure was developed using already established tools in the form of commercial software products in order to facilitate transfer to real design tasks and to ensure the practical applicability of the method. Elementary component of the procedure is it to support the developer with the production of the rough shape of the product and to achieve at the same time a tool-spreading illustration of the information gradually produced. The designer should be supported in the creative problem solving process and relieved by the partial automation of complicated or time-consuming data processing steps. The core components of the approach are the continuous data maintenance of parametric die surface features as modular information units and the consistent further use of the attributes defined by the developer step by step.
The following figure shows a schematic representation of the desired approach.

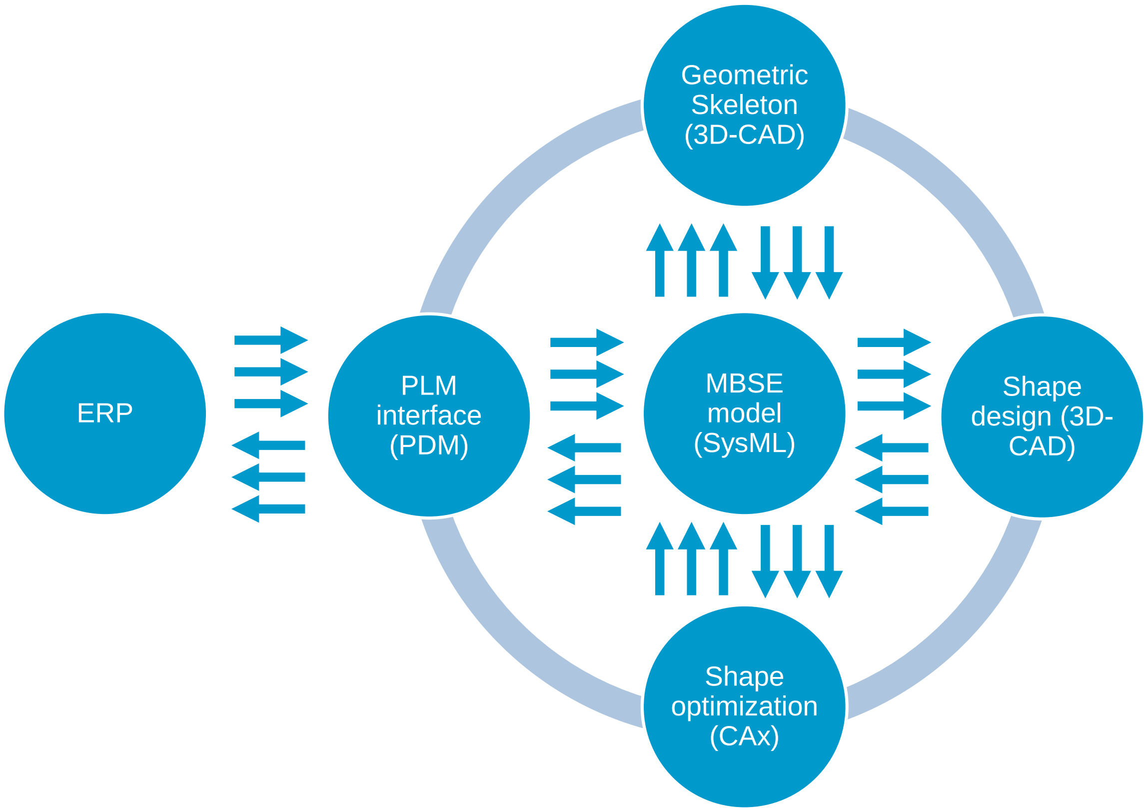

Figure 1: Concept of methodological cross-domain approach

The focus is on the system model as a knowledge store and information technology reference. Information from the expert domains is fed into the MBSE model during the product development process. On the other hand, the system model feeds the participating expert tools with necessary information, as far as these are available in the system model. All circles shown stand for individual information instances of the product model. Accordingly, the MBSE model functions in the approach presented as a backbone in the product development process.
In the following section, the method presented here is transferred to the concrete tool domains.

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3.2 Transition to the tool domains

Due to the very different infrastructure in industrial companies, the following assumptions are initially made for the tool domains:

- A parametric CAD system is available
- An MBSE modelling tool is available
- A PDM system is available (coupling with CAD system optional)

These conditions are often found in medium-sized to larger companies. In practice, it can be seen at first glance that MBSE modelling tools are rarely or not at all used in product development. However, these tools are used relatively frequently in the internal IT development departments. The author also assumes that MBSE and system modelling will play an increasingly important role in development in the future.

The following figure shows the integration of the individual tools into the product development process according to the proposed method. The upstream phase of product planning is assumed to be given in this approach. The core component of the approach presented is the continuous data maintenance of parametric working surface features as modular information units. This should ensure a consistent further use of the attributes defined by the developer step by step beyond the tool boundaries.

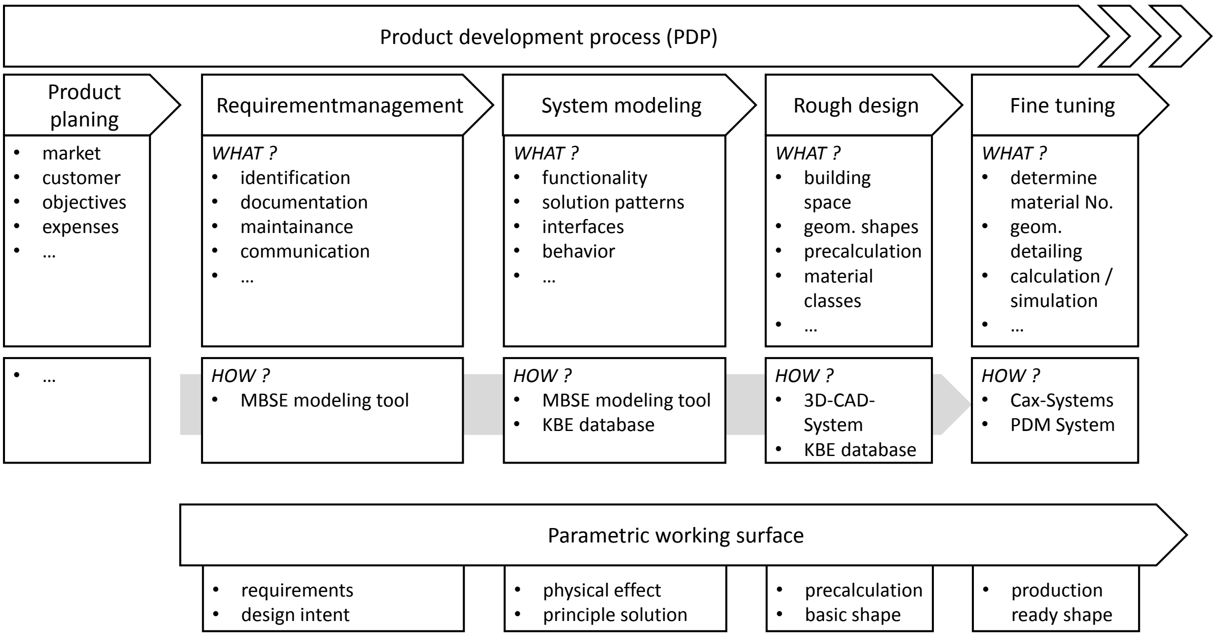

Figure 2: Concept of parametric working surfaces in the context of a PDP

The process shown here is not to be understood as a stage-gate-process or waterfall model. Within the methodology, as well as in real projects, it is possible and useful to iteratively jump back and forth between individual process phases. Rather, the core of the method is to anchor the generated or revised information to a data object: the parametric working surface. As shown in figure 1, the MBSE model should act as the connecting instance. The PDM system also serves as an interface to the subsequent production and enterprise processes.

Unfortunately, a complete integration of MBSE modellers, 3D CAD systems and PDM systems is not feasible at the current state of the art. On the one hand, this is due to the policy of the software manufacturers who do not want to agree on a uniform transfer standard in the sense of a data format. On the other hand, the tools have very different information architectures. Therefore, the information cannot simply be completely transferred to the tools. A reference level is needed that provides suitable information for different tools. In principle, a PDM system would be suitable for this. However, the method presented addresses the task of redesigning a mechanical component.

Due to the processes for solution finding and design, it is often necessary to adapt the class attributes even after instantiation of objects (i.e. at runtime). The consideration of the parameters level (e.g. physical effect, analytical models, etc.) also plays an important role for the developer in the development of new solution approaches. Here MBSE modellers offer more attractive possibilities

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than conventional PDM systems (e.g. parameter studies). Therefore, the proposed method uses the MBSE model as information center for the development phase.

In order to overcome the difficulties of data synchronization, intermediate states of the system model (so-called model instances) are provided in the form of a *.html portal. The individual tools can then reference the system information using a hyperlink. If the html instance is available in the company intranet, all developers involved in the process can access the information stored there. Information from the tools can also be linked in the system model. This avoids time-consuming agreements and mutual data reconciliation. On the other hand, with this method a responsible administration of the system model as a central information connector is decisive.

According to figure 2, the information of individual design elements is linked to parametric working surfaces. A pair of two working surfaces is required to implement a physical effect. This corresponds to the logic of the contact channel approach established in research. In the MBSE model the parameter-related information (e.g. transfer functions, efficiencies, etc.) is stored, while in the 3D CAD system the geometry-related information is modelled. At the beginning of the new design, for example, the maximum installation space and the location-related position of the external interfaces are defined here. The thus excellent information on the working surface pair, or on the single working surface from the point of view of the individual component part, then forms the starting point for the geometric design of the component geometry. For this purpose, predefined working surface geometries are selected from a repeat library according to the approach of knowledge-based engineering and inserted at the interface position of the skeleton model in the CAD tool. In the process, so-called product manufacturing information (PMI for short) is used to attach reference markings to the die surface. These contain the already defined information in edited form (e.g. physical effect, input, output), but at least one hyperlink to the corresponding element in the system model. This serves the traceability of the elements of the basic geometry. Subsequently, the shape finding can be carried out according to known methods (e.g. topology optimization, Boolean operations, surface fusion, etc.). The following illustration shows an example of the process of shape finding with different methods.

The modelled installation space serves as the maximum material limit. The basis shape of the die faces and their meta attributes can be used to define non-design-areas and boundary conditions for numerical form optimization. The PMI information can be inherited via formula functions as component properties. These part properties are available as part attributes in the PDM system. For this purpose, the data classes of the PDM system may have to be adapted once (e.g. extension of component properties by physical effects).

The described method allows to connect common tools in a pragmatic way. Due to the universal character of the html portal, this approach allows the linking of software tools independent of the manufacturer. By networking and mapping the information in the MBSE model and the tools, the development information is transported and identified throughout the entire PDP. In the following section, the implementation of the parametric working surface method in the 3D-Cad system will be discussed in more detail.

4 DEMONSTRATOR

In the following an exemplary application of the presented method on a fictitious component is explained. Research results from Ersoy, Koller and Ashby as well as observations according to Feldhusen were used as the basis for the implementation. For reasons of secrecy, the diagrams and components were alienated, whereby the core statements are still given.

Ersoy's work has resulted in empirically determined effective surface geometries and pairs (Ersoy, 1975, pp. 135 et seqq.). Within the concept presented, these form the geometric basis of a generic working surface feature. Since Ersoy did not address the functional relation to the working surface geometry (Ersoy, 1975, pp. 37), the Koller approach is used to create a link between the working surface geometry and a principle solution or the underlying physical effect (Koller, 1998, pp. 2 et seqq.).

According to the definition of Feldhusen, knowledge of an effect carrier is also necessary in order to develop a specific principle solution (Pahl and Beitz, 2007, pp. 181 et seqq.). The classification of the materials according to Ashby (Ashby, 2005, pp. 27 et seqq.) is used in this work. Due to the very early phase within the product development process, only the predefined upper classes of the material groups are used (e.g. metals, polymers, ceramics).

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4.1 MBSE model

At the beginning of the PDP a MBSE model was built with the software Cameo Systems Modeler 18.5. This system model has been created based on the SysML language. The following figure 3 shows the functional structure of the system in a SysML notation within a block definition diagram. Here, the main function of the profuct and secondary functions of sub-assemblies or sub-parts were derived as own stereotypes from the general block stereotype. The component-specific functions were combined in a package. The requirements were subdivided into superior requirements, requirements and sub-requirements and assigned to the related functions.

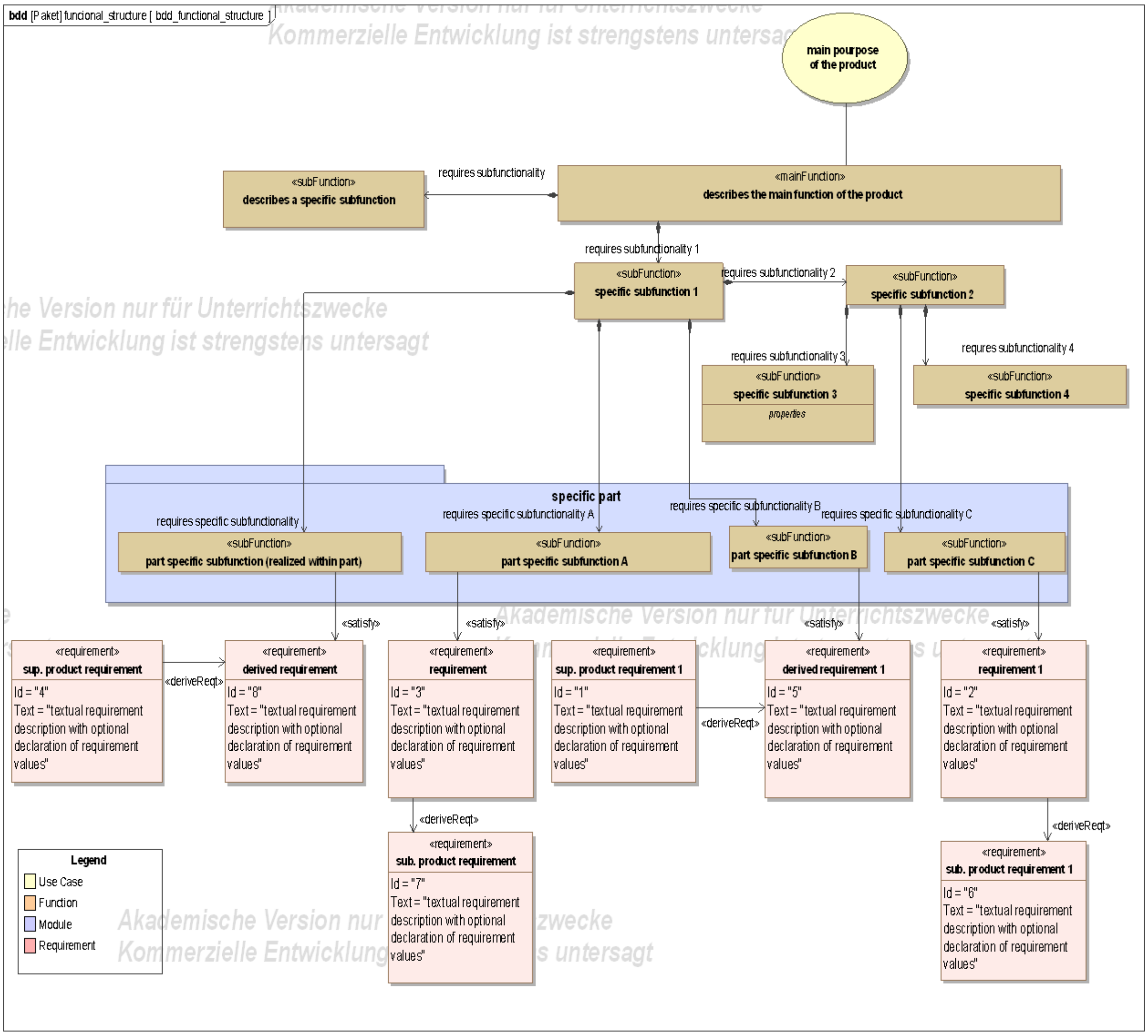

Figure 3: Functional structure in the MBSE model

In addition to the functional structure, parameric diagrams of the principle solutions (e.g. transfer behavior of the physical effect) were also included in the system model. These "simulation models" can be executed within the modeler software, so that a change of the input values of a principle solution causes a response on the output page. By linking requirement values with parameter values, it is possible to estimate how individual solution combinations influence the overall result during the concept phase. For this purpose, several principle solutions were prepared in a solution library based on Koller and Ersoy.

On the basis of this model-supported concept finding, the function synthesis can be planned up to the principle solution determination in the MBSE model on parameter level.

The next step is a shape definition in the 3D CAD system with transfer of the attributes to the PDM system.

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4.2 3D-CAD-system and PDMS

Every principle solution of the MBSE model is based on the interaction of two working surfaces according to the contact channel method. After statistical investigations, Ersoy proposes 30 basic geometries which can be combined to 90 different configurations. Each configuration therefore has special kinematic degrees of freedom in space. In the demonstrator tool, some of these working surfaces were created exemplarily in the form of user defined features in the 3D Cad system. In addition to the pure geometry, these features also contain the relecant metadata of the principle solution (e.g. physical effect, material class, input variable, etc.).
Based on the information of the MBSE model, the CAD system first determines the installation space and the interfaces for a component design. Then the parametric working surfaces from a repeat library of the CAD system (here: Siemens NX 11.0) are inserted at the interface coordinates and oriented to the surrounding components according to the specifications of the system model and the kinematics.
The following figure 4 shows an example of a component design in the 3D-CAD-System. The working surfaces of the part body were marked in red color. The corresponding attributes have been selected manually in the form of Expression formula, shown in the window “expressions” in the upper area of figure 4. In the presented example, the attribute value corresponds exactly to the MBSE model specification. The Expression fomula are also optically displayed as PMI, vizualised with dashed lines in the presented figure 4. In addition, the expression formulas are also inherited as part attributes. The part attributes of the 3D-CAD-system are displayed in the left area of figure 4. This transfer of the properties of the working surfaces from the expression sets to the components attributes can then be used in the PDM system to show these informations of the component.

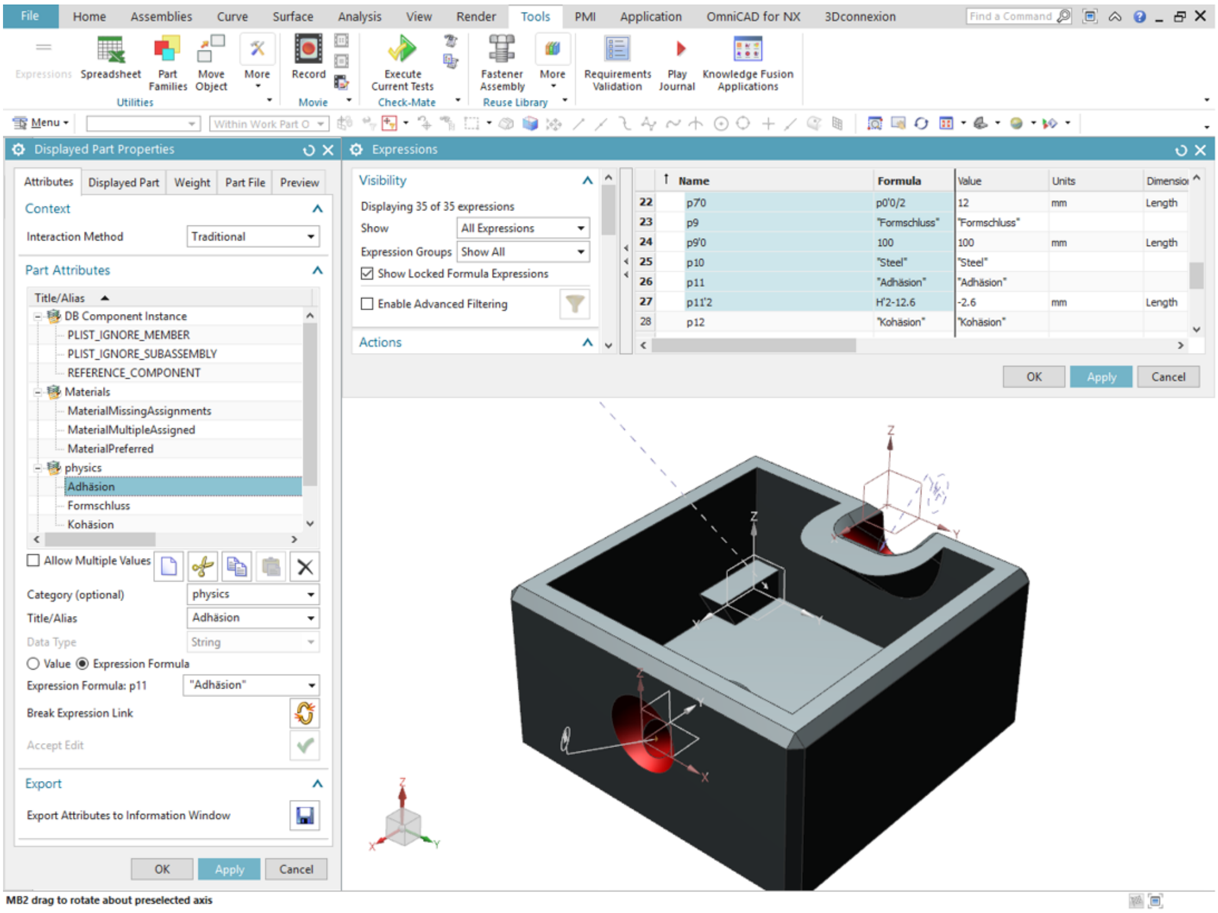

Figure 4: Example part model in a 3D-CAD-system

Aside of the information transfer into the PDM system, additional intelligence has been added to the CAD system by the following techniques. One of the meta attributes of each working surface is a hyperlink to the published html system model instance as stated in chapter 3.2. Activating this link opens up the corresponding informations in the html system model instance using the standard OS web browser. The PMI, the coloured surface and the hyperlink formula provide explicit information

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about the relevant working surface areas on the part to the CAD user. Given the appropriate permissions to access all tools, a design engineer can thereby access the information in PDMS, 3D-CAD and MBSE model in a self-reliant way.
Applied to industrial applications, this means that all information is available to the developer at all times, regardless of the company's geographic location or specific department. Consequently, the information flow between the system engineer, the design engineer and other involved domains during the product development process is realized on a consistent data level and the need for active information exchange between the process participants can be minimized. In addition, the design intention is also explicitly marked and therefore permanently transparent in later phases of the development process.

5 OUTLOOK

Within this paper, a MBSE toolchain concept for product design with the Method of parametric working surfaces has been presented. The approach is applicable to common software tools in professional engineering design due to its hyperlink based data connection structure. By synchronizing the information in a MBSE system model, a 3D-CAD-System and a PDMS, the self-reliant agility of design engineers in concurrent development projects is enhanced.
Due to the underlying hyperlink concept, the approach requires a regular maintenance of all data status. Therefore, future research has to be carried out to determine suiting role models for PDP. The maintenance of a MBSE system model has not been in focus of engineering design processes until the past years. However, similar developments in the IT domain and exemplary approaches in the aerospace industry show promising results for future application in general engineering design.
The inclusion of a MBSE model into shape definition processes enables the engineer to rely on parametric interrelations of geometry and shape on an analytic level. This requires sufficiently detailed principle solution information in terms of predefined kits that can be generically used in development projects. This approach has allready shown great success in the past with 3D-CAD-Data libraries of standard parts and supplier parts. Implementing such libraries with MBSE sub-models and related simulation models will be of great use for concept design of products in the future.
While the general approach has been demonstrated with a single product development process and a specific toolchain within this paper, the method still has to be evaluated against a representative quantity of product development cycles to prove its robustness in real industry use-cases.
The discussed research questions are investigated by the authors in ongoing research projects.

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