FUNCTIONAL SURFACES AS INITIAL PRODUCT DESIGN CONCEPT IN 3D-CAD-SYSTEMS

Katzwinkel, Tim; Jacobs, Georg; Löwer, Manuel; Schmid, Alexander; Schmidt, Walter; Siebrecht, Justus
RWTH Aachen, Germany

Abstract

Finding an initial shape design for innovative product concepts is one of the most challenging and most creative parts in product design processes. To support design engineers during that particular phase, knowledge based design automation tools can be used. This paper proposes an enhancement of existing design methodologies in terms of initial shape design of innovative product concepts.The presented approach consolidates PLM and parametric 3D CAD technologies into one integrated method. A concept of parametric working surfaces as an institutionalized feature embedding product lifecycle knowledge is described and briefly demonstrated with a software example. The approach intends to support the product designer with additional information from different company departments as well as giving the designer a tool to explicitly declare the design intent of its design concept in the very early phase of geometric shape definition.

Keywords: Computer Aided Design (CAD), Design methods, Knowledge management, Virtual Engineering (VE), Product Lifecycle Management (PLM)

Contact:
Tim Katzwinkel
RWTH Aachen
Chair and Institute for Engineering Design
Germany
katzwinkel@ikt.rwth-aachen.de

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1 INTRODUCTION

When creating innovative product concepts, there is a first design phase for every new development of mechatronic products. In this phase, the analytically and/or theoretically determined requirements, physical effects, solution principles and feature properties of a product concept have to be converted into a discrete first geometric form. In the context of this contribution, this phase is called "initial design". Figure 1 shows the integration of the initial design phase in the early phases of a generic product development process.

In the field of system engineering, various existing solutions can be reused as templates or implemented as partial solutions to fulfil an overriding purpose. For example, partial functions can be realized by using purchased parts (e.g. automotive supplier) or standard components (e.g. machine elements). In contrast, in the case of an innovative part design from scratch no existing geometry can be referenced. Therefore, a first coarse shape of the part geometry has to be defined individually by the design engineer. Today's established design methods lack of strategies for the systematic and knowledge-based transformation of the theoretically developed product concepts (e.g. function structures, product structures) into a discrete first geometric shape in a standardized and tool based way (Tomiyama et al., 2009).

In the past, a lot of efforts have been made in automation of design embodiment tasks in the field of requirement engineering, system engineering and knowledge-based engineering. The problem of shape finding within product design tasks has been addressed in the recent past, even though approaches concern descriptive information enhancement and recombination of existing geometric patterns (Hoisl and Shea, 2013). In respect to the capability of today’s 3D-CAD-Systems and their strong integration in product lifecycle management (PLM) environments, the automation of the initial design phase in product development processes seems a consequent enhancement of design automation approaches.

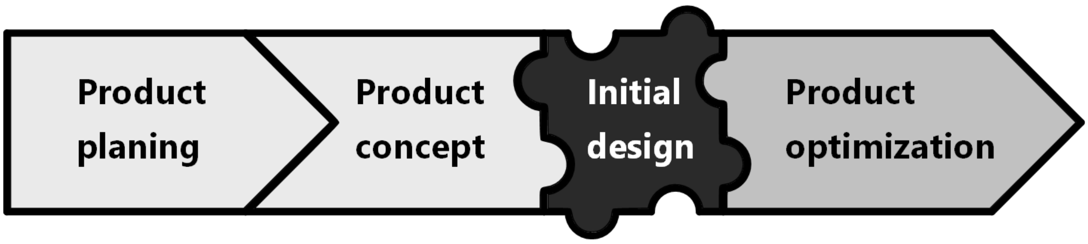

Figure 1. Initial design phase in a generic product development process according to Pahl and Beitz (Pahl et al., 2015)

Compared to heuristic approaches in initial design, the methodical anchoring of working surface definition within the PLM environment bears a high potential for a sustainable and continuous assistance of the product designer throughout the whole product development process. The novel approach to initial design shape synthesis proposed in this paper is a combination of knowledge based engineering and working surface modelling with a PLM based data integration.

The working surface not only represents the initial product geometry but is enhanced with parametric information through the PLM-backbone (e.g. physical effect, fulfilled product function, calculation parameters). With a connection to PLM the interdependencies between shape design iterations and product characteristics in terms of solution quality, producability and economical aspects get computable. This is an important step to bring design automation into the described initial design phase. Modern product developments and innovative design concepts are often realized in a collaborative framework of different company departments (e.g. engineering, manufacturing, purchasing, sales, service) as well as multinational facility units. The challenging task of collaborative engineering throughout departments and facilities in the initial design phase can be enhanced by standardized and exchangeable design features as well. In addition, defining the initial product shape with respect to the known restrictions from all involved design domains has the potential to improve the efficiency of common design tasks by reducing the amount of necessary iterations to define the most feasible and economical product concept.

2 STATE-OF-THE-ART

In recent decades, the systematic development of products has been intensively researched. Various design methodologies and guidelines have been developed. Pahl and Beitz introduced a model that systematically links individual activities during a product planning and design process and maps them with additional consideration of a time component within a definite course of action (Pahl et al., 2015). This process consists of four main phases starting with the assignment of the overall task and ranging to the discrete solution, while the course allows unavoidable iterations in practical use and has been implemented into the well-known guideline VDI 2221 (VDI, 1993). 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 function-behavior-state model (FBS) of Umeda et al. focusses on the different aspects of physical effects depending on the engineering viewpoint (Umeda et al., 1990).

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).

Due to the rising capacities of computer automation as well as the affordability of software tools and hardware components the research topic of design automation has been intensified lately. According to Rigger a lot of research effort has been made in task categorization and method selection as well as system architecture design and optimization (Rigger et al., 2016).

According to Pahl the systematic approach to a product design concept involves first the selection of one or several physical effects that realize the desired functionality. In a following synthesis step the principle solution to a specific function is found by determining the effect carrier (material) and the geometry of the effects location. The physical effects are then applied through the working surfaces of the specific components (Pahl et al., 2015).

In terms of knowledge-based engineering approaches principle solutions can be derived from various design catalogs. Knowledge databases (design catalogues) offer a preselection of the possible combinations of effect, the effect carrier and the concrete geometry shape (VDI, 2004; Koller and Kastrup, 1998).

The decomposition of components and subassemblies by means of their working surface pairs has proved its worth in methodical analysis of technical systems since the 1980s in design methodology research and is known as the contact channel method (c&c-m). In combination with the known requirements to the product a statement about the behaviour of the entire system and individual components (e.g. deformation analysis, dynamic loading, jamming of components) can be made. In addition, suggestions for improvements can be proposed by identifying the cause-effect chain and its weak spots (Ersoy, 1975; Rodenacker and Claussen, 1973).

Roth stated the theory of working surface pairs and the channel and support structures to be fundamentally the point of origin for initial shape design (Roth, 2000).

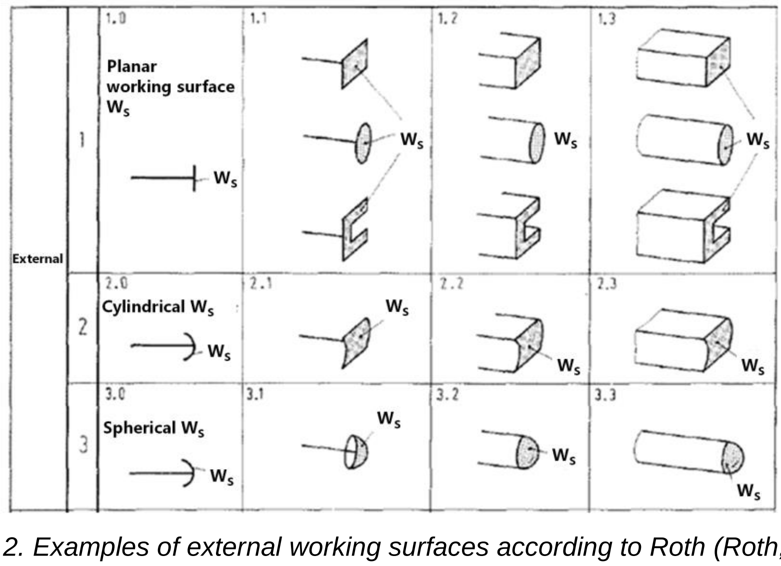

Figure 2. Examples of external working surfaces according to Roth (Roth, 2000)

Matthiesen proved the contact and channel method to be particularly suitable for the determination of an intial component shape as well (Matthiesen, 2002). In order to ensure an efficient concept design, Lemburg enhanced those approaches by proposing a step-by-step shape determination (Lemburg, 2009). The c&c-m approach was intensively extended regarding the component analysis and optimization of already existing structures and partial solutions by Albers and Matthiesen (Albers and Matthiesen, 2002). They continued the described approaches and developed the "Contact and Channel Approach" (c&c-a), which can be used to analyse functional and creative relationships with existing components, assemblies and products. The developed methods have primarily been used for system analysis and optimization in terms of quality control and design optimization (Albers et al., 2011; Albers and Zingel, 2013; Albers and Wintergerst).
The c&c-m approach has rarely been used systematically in new design tasks without existing product geometries that can serve as templates. In design automation few approaches for computer-aided initial geometry generation and modelling strategies for modern three-dimensional computer aided design systems (3D CAD systems) in that context are known (Foucault and Léon, 2010; Hoisl and Shea, 2013).
In the presented paper the question of how to use the working surface and channel and support structure theory for the initial shape design in new constructions is addressed. According to the authors, the applicability must be seeked through a contribution to the main tool of the product designer during the very first definition of components geometries: the 3D CAD system. This enhances the efforts in computer aided conceptual design shown by Lemburg (Lemburg et al., 2007).

2.1 3D-CAD-Systems

Since the end of the twentieth century, CAD has been widely used in a broad range of industries and application fields. Within the scope of this paper, the modelling of product concepts and geometric prototypes is particularly important. However, the data generated can also be used for further analysis and calculation methods such as multi-body simulations, finite element analyses or flow simulations. Due to this extensive and complex networking of the generated geometry data with many optimization processes and different engineering domains within the product development, the efficient generation of geometric data in a high quality is particularly important (Vajna, 2009).
The modelling of geometric product data in 3D CAD Systems can take place via different modelling strategies. Line modelling, surface modelling and volume modelling can be distinguished (Pahl et al., 2015). For the generation of three-dimensional geometry information, most expert systems today use a combination of these modelling strategies. The volume modelling is carried out using boundary surface models (B-Rep) or the composition of new volume bodies made of simple standard bodies which is called constructive solid geometry (CSR). Current 3D CAD applications use so-called Hybrid models, a mixture of CSG and B-Rep (Eigner, 2014).
The modelling of a three-dimensional component can be carried out with the aid of controllable parameters and a traceable change history, the so-called parametric modelling. However, geometric elements can be modified directly by manipulation of the local component geometry, without renouncing the parametrizable changeability of the generated model. This approach is also known as direct modelling. While the advantage of parametric modelling is the controllability of the model and the good handling of complex components and assemblies, the direct modelling approach provides a fast and very flexible model adjustment. Today's CAD systems usually offer both modelling methods and also enable combinations of these (Pahl et al., 2015).
While the methods of direct or parametric modelling address the general geometry generation for a component, recurring function elements of a certain design feature are usually realized by predefined design elements. These elements include bore, chamfer, radius, rounding, thread and more. This approach is also called feature-based modelling (Eigner, 2014).
In addition, various strategies and processing sequences have been used to consider an economic planning and organization of the modelling during the transition from the concept phase to the design phase. For example, product-oriented modelling ("top-down") or component-oriented modelling ("bottom-up") are known, in which the product is structured according to a planned product structure or by successive modelling of individual parts. In addition to the product structure, the product space can also be defined in different ways. In the "outside-to-inside" modelling method, a three-dimensional enclosing envelope (for example, a maximum installation space) is determined which cannot be interrupted during product modelling. Subsequently, components and assemblies are designed into this envelope. In the complementary method "inside-to-outside", the enclosing space results from the

modelling of single components and their grouping. Depending on the application, the presented methods are combined. For example, a "top-down" modelling "outside-to-inside" is recommended for the redesign of complex overall products. In contrast, a "bottom-up" modelling " inside-to-outside" is used for the development of fluid technology components (Vajna, 2009).
The visualisation of individual parts and assemblies can be carried out in 3D CAD systems in a detailed or simplified manner. The simplified representation forms can serve to increase the computing performance or, for the first functional design, to roughly define the essential design features. Although the simplified representations have not been standardized to a large extent, there are separate rules for the 3D representation of standard parts. For example, DIN 32869 provides simplified and standard CAD drawings of standard elements of mechanical engineering, such as rolling bearings, coil springs, screws and nuts (DIN, 2011). In addition, DIN 4003 defines basic elements in three-dimensional space (coordinate systems, planes, axes and points) for the 3D-CAD modelling of tools and machine tools (DIN, 2014). Despite these isolated rules for the representation of standard parts, there is no uniform set of rules for generating initial product geometries of previously untapped technical solutions yet.

2.2 Product Lifecycle Management

In respect to the diversity of different organizational domain influences during the product development process the knowledge-based strategy of product lifecycle management has to be respected in the presented context. According to Feldhusen product lifecycle management (PLM) is a knowledge-based company strategy for all processes and their methods in respect to product development from the first product idea up to the recycling of the product. Similar to the entire product development process, the initial product design process is also an information processing procedure. Input information must be available for each single design phase, and then be aggregated, processed, expanded and ultimately maintained for further synthesis steps. The concept of the intrinsic product life cycle has therefore become established for a comprehensive description of a product with all its methods (Pahl et al., 2015; Feldhusen and Gebhardt, 2008).
In relation to the entire product portfolio of a company, this results in the need to implement a strategy involving all areas of the company. In the sense of a matrix organization, the task area corresponds to a cross-section function, which must ensure and amplify the synergistic and useful effect by networking the departments and experts involved in the respective lifecycle phases of the product. However, it is important to note that PLM can include not only the processes within the company itself, but also the interactions with customers, cooperation partners, suppliers and the entire supply chain.
The entirety of product, product data, tasks, methods, supporting tools, organizational structures, as well as the employees and / or personnel resources involved, is referred to as Product Lifecycle Management. According to Stark the efficient connection of all those aspects is the main task of PLM (Stark, 2016). The digital image of the company and product knowledge is a central component of the PLM and thus the basis for the modeling of complex company processes. In doing so, entities and properties of a product concept as well as its associated processes and corresponding roles in the specific organizational structures become manageable. A particular challenge for Product Lifecycle Management is to integrate information sustainably into the product development and manufacturing process in order to enable innovation management in the sense of the systematic planning and control of innovations by means of structured processes (Arnold et al., 2011). In view of the growing innovation potential, more and more companies are calling for agile and flexible PLM modeling strategies, which is only possible to a limited extent due to the blurring of fast and short product development cycles with today's modeling strategies.

3 WORKING SURFACE MODELLING AS A DESIGN CONCEPT

3.1 Analytical approach

Well-established product types and standard machine elements within industrial products consist of different types of working surfaces, a channel and support structure connecting pairs of working surfaces and remaining additional structures that have minor influence on the fulfilment of the products functions. On the one hand the working surfaces can directly be related to specific functions that have to be realized with particular geometry to ensure the product purpose. On the other hand a co-dependency between manufacturing restrictions, customer requirements or special market demands and the specific surface geometries are comprehensible. By analysing established products in respect to their overall purpose,

the underlying functional structure as well as the resulting product structure and the manufacturing restrictions within the producing companies, the identified working surfaces of a product can be categorized into different quality levels.
For example, the decomposition of working surfaces concerning a common ball-bearing reveals different kinds of working surfaces (Figure 3). While the main function of reducing rotational friction as well as the support of radial loads is realized with cylindrical and spherical working surfaces, the support of axial loads can be geometrically reduced to planar working surfaces. In this simple example side functionalities (e.g. sealing, lubrication) have not been considered.

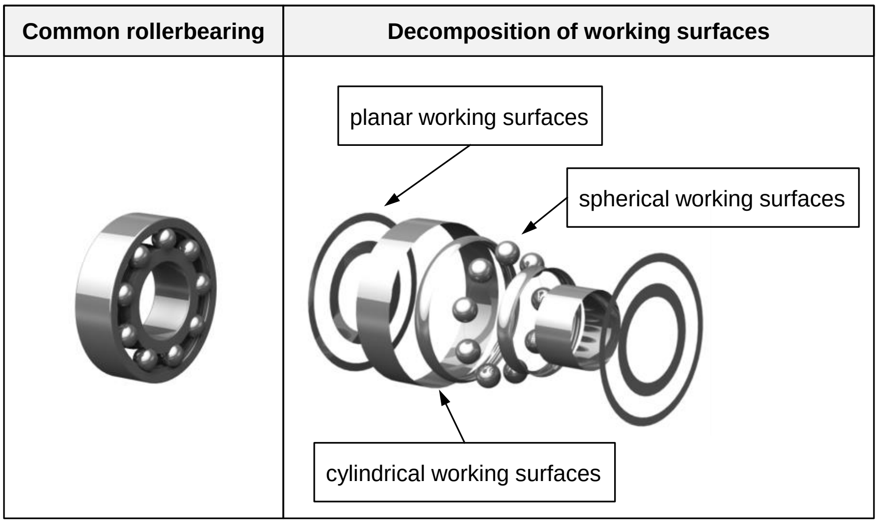

Figure 3. Example of working surfaces decomposition in 3D CAD Systems

From the mechanical engineer's point of view the choice of planar, cylindrical and spherical working surface geometries out of all possible surface shapes can be reasoned with the main functional operation of radial transmission of motion and in the meantime reduction of rotational friction. From the manufacturer's point of view the planar, cylindrical and spherical working surfaces are simple, cost-efficient producible geometries. However, other well-established industrial solutions are known to fulfil the same purpose (e.g. slide bearings in place of ball-bearings, polygon profile connection in place of cylindrical working surfaces). In order to evaluate the most suitable solution approach, the underlying physical effect, influences of the effect carrier, the shape of working surfaces and the requirements resulting from the external restrictions must be equally taken into account during the concept development. Since the product developer is already working in 3D CAD systems with parameter-based control in the design definition, it seems obvious to utilize these tools during initial shape design synthesis.

3.2 Method of initial design shape synthesis with parametric working surfaces

In product development, finding an initial design shape is one of the most challenging tasks during the design process of innovative products. In contrast to variant design tasks, the initial geometry shape cannot be adopted from existing solution variants when designing new innovative products from scratch. In addition, the quality of the function fulfilment depends on the implementation quality of the selected physical effect and thus directly on the working surface geometry. Finally, according to Pahl the design of new products is a process with several iteration steps (Pahl et al., 2015). Within each single iteration the requirements and restrictions to the design task may concretize which can result in adjustment of the effective structures and thus adjustment of the working surfaces geometries. Changing the working surface geometry might influence the implemented physical effect (e.g. degree of efficiency). Therefore, the product designer has to verify the efficiency of the design concept after each iteration and prove that the concept is still valuable. Today, design processes can be highly collaborative and distributed to several locations. Consequently the validation of each iteration loop requires continuous control over all design aspects as well as the integrity of the produced data.
To overcome the described problem of initial shape definition and to gain more control over the specific iteration loops during the design process, this paper proposes the implementation of parametric working

surfaces as an extension of the design methodology according to Pahl and Beitz. As is shown in Figure 4, the design process is expanded by the concept of parametric working surfaces.

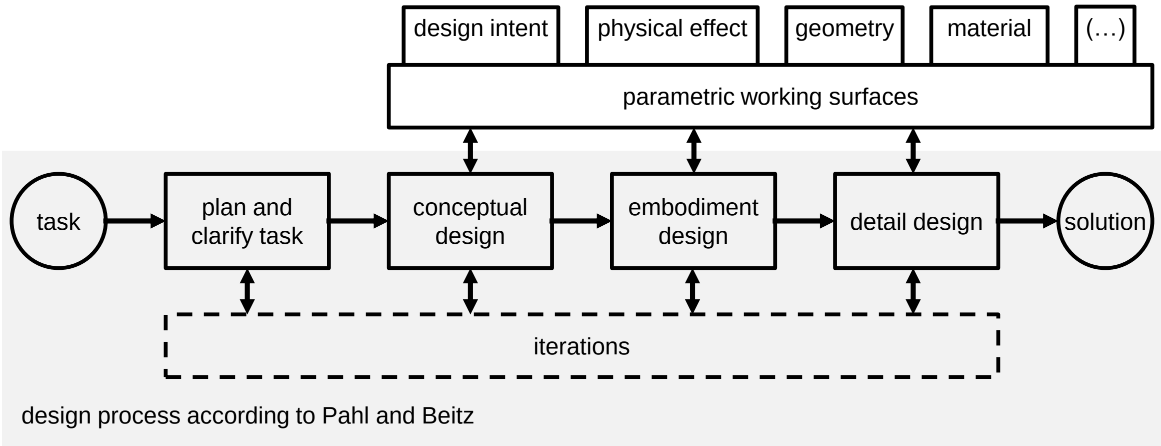

Figure 4. Enhancing the design process according to Pahl and Beitz by parametric working surfaces

Representing just a standardized rough geometry shape during the conceptual design phase, those initial geometric units contain the core information of the chosen principle solution for the discrete product function that is fulfilled (e.g. physical effect or material restrictions). Thereby the design intent of single surface geometries is predetermined during the initial design phase. In terms of collaborative product development all involved product designers can access the information and no longer risk to accidently downgrade an existing solution by manipulating geometry shapes that influence the underlying physical effect (e.g. reducing the surface area of a working surface using the adhesion effect). The parametric aspect of the concept addresses the interdependencies between external and internal requirement sets (e.g. customer, law restrictions, manufacturing restrictions, physical limitations) as well as the characteristic values of the initial solution concept that extend the pure geometry information. The presented method is based on the idea of predefining the concept basics within the initial design phase. In further iteration steps, the parameter set can be enhanced and the parameter values may change. However, the reference to the initially defined parametric working surface remain the same.
The idea of the presented method is borrowed by the standard feature of product manufacturing information (PMI) in common parametric 3D CAD Systems. While the connection of additional information to certain spatial geometry is state-of-the art in those software tools, the parametric relationship of PMI and product concept attributes or requirements and their influence to the design concept quality has not yet been addressed. The implementation of the presented approach a standard feature in 3D-CAD-software seems to be a necessary upgrade of the PMI capabilities.

3.3 PLM-integrated knowledge based design intent

PLM environments provide the possibility of enhancing knowledge based engineering. This includes material databases, catalogues of physical effects, part specific requirements, manufacturing restrictions and other possible influences to the design shape. Within the presented approach the implementation of the parametric working surface within an existing PLM-environment is aspired. Thereby the initial design intent (e.g. physical effect, geometry, material) can be enhanced by the influences from other departments (e.g. manufacturing restrictions, supplier restrictions, buying restrictions). Figure 5 illustrates the PLM-based completion of the discussed concept of parametric working surfaces.

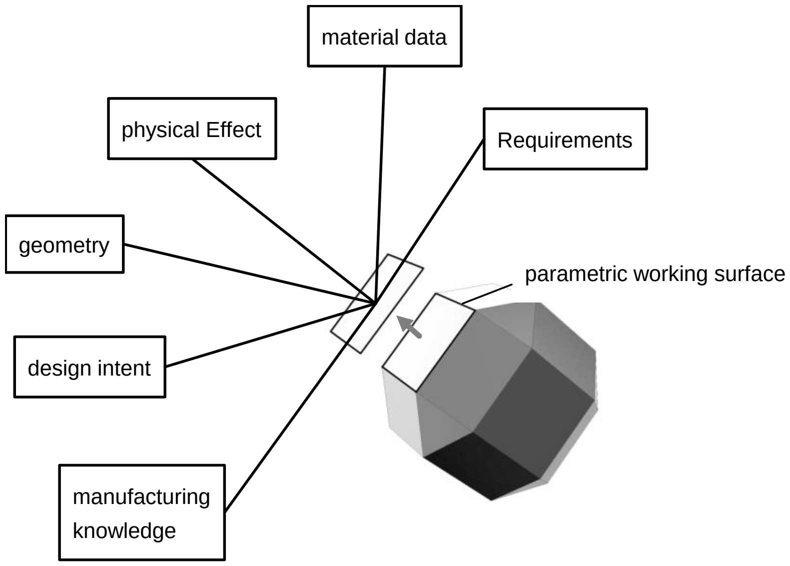

Figure 5. PLM-based knowledge conjunction within parametric working surfaces

The integration of external data into the 3D-CAD-modelling process with the aim to improve the design concept has been proved useful by Siemens PLM regarding the HD3D-Visual-Reporting feature of the CAD-System Siemens NX. The feature allows the survey of the geometric model compliance with requirements, design standards and quality guidelines defined in the PDM-software tool Teamcenter (Siemens PLM, 2016). While this specific solution addresses primarily the discrete spatial geometry and visual feedback for the designer to avoid noncompliance to company standards and cost driving design concepts, the described extension of the design methodology has potential to bring additional benefit into the initial design phase as presented in Section 3.2.

4 SOFTWARE DEMONSTRATOR

To demonstrate the potential of a methodical implementation of working surfaces definition in early product design phases a software plugin has been developed using the common application programming interfaces (API) of a well-established parametric 3D-CAD-System (PTC Creo 2.0 parametric). The demonstrator focusses the aspect of declaring explicit design intentions into early product concept geometry. The plugin is relying on an external database containing function related information about surface properties based on the withdrawn VDI/VDE 2106 (VDI/VDE, 1991). Designed as a standalone executable file, the plugin software can be connected to *.prt- or *.drw-files that are used in a running creo 2.0 instance. The software uses the official “PTC Creo VB API Type Library for Creo Parametric 2.0”. To provide working surface depending design catalogue knowledge to the user, the software uses additional XML-based data files. The data from the XML-Files is initially loaded into RAM disk when using the plugin for the first time. Then, it can be adjusted and enhanced according to the specific use-cases (e.g. user input). After specifying the working surface information, the data is then saved into the *.prt-file itself. Any further changes to the knowledge information are performed by connecting directly to the *.prt-file, which still can be used in common ways by the designer (e.g. derive drawings within creo). Technically, the part file is enhanced by additional source code lines at the end of the original code. In the following passage, the functionality of the software is described in detail.

Using the software plugin, every existing geometric surface within the creo file can be addressed. The product designer is enabled to define the purpose of all geometric surfaces within the generation of early design concept geometries. It is possible to declare the design intentions of each working surface through the plugin interface as well. In a first step, the user has to predefine the discrete purpose (function) of the working surface. Therefore, a surface has to be selected manually and then can be given user defined informations (e.g. name, design intent, special properties) as is shown in Figure 6. In the next step, a linked external database is consulted to find known restrictions for the defined purpose (e.g. necessary surface finishing to realize a sealing surface of a certain quality).The database provides a set of predefined working surfaces and their recommended properties which can be of course enhanced by the user. Additionally, the database is extendable and can be filled with company specific data by editing the XML-files. In the last step the information is permanently connected to the surface geometry through the plugin. All the generated information is saved within the original part file and can be handled through the plugin (e.g. adjustment, deletion). The part file format itself is not violated by the plugin and therefore can still be used in common workflows. For example, additional notes according to the specific design intent can be imported into a derived drawing.

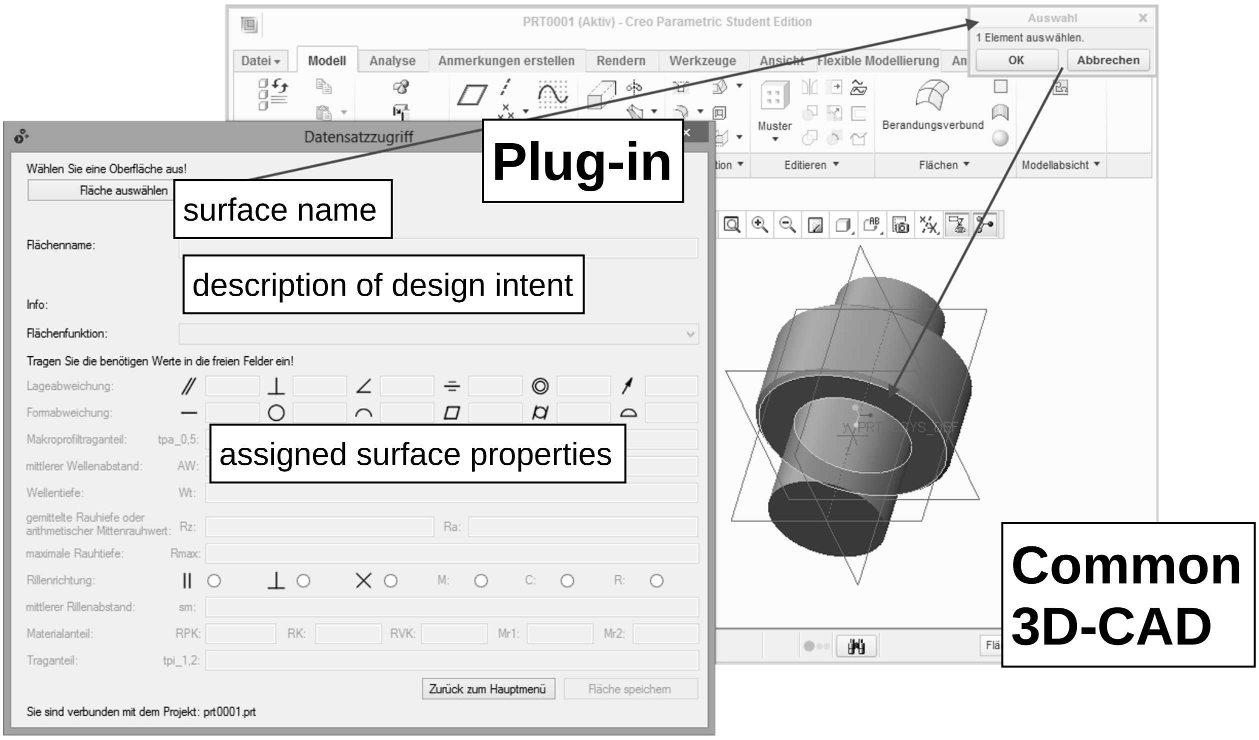

Figure 6. Definition of design intent related to functional surface modelling with a Software-Plugin

Changes done to a defined working surface with a discrete purpose result in a warning message. Thereby the product developer is reminded that the desired iteration of the working surface will affect the predefined purpose. The assigned properties of the working surfaces can be forced to be mandatory as well. In that case the user will be forced to apply the related values before he can continue his work. The implemented information enhancement can be exchanged between different users by simply exchanging the creo file itself as the information is coded within the file's structure.

The software plugin provides an improvement of established workflows by avoiding accidently changes to working surfaces with predefined design intent. At the same time, knowledge from an external database is provided to the shape designer. Finally, each working surface has to be declared regarding its design intent (e.g. physical effect) and can be enhanced with additional information according to the described PLM approach (e.g. manufacturing restrictions, tolerances, material).

5 SUMMARY AND OUTLOOK

To address the problem of initial design shape definition in common product development processes a systematic approach based on today's 3D CAD Systems and PLM environments has been proposed. The concept of parametric working surfaces as an institutionalized 3D CAD feature with embedding in PLM-Methods has been described and briefly demonstrated with a software example.

The feasibility of the software has to be proved in future experimental studies. In further research steps, the integration of knowledge based methodical approaches to product design will be examined using the catalogue of physical effects by Koller (Koller and Kastrup, 1998). Furthermore, the influence of top level requirements to the initial design phase will be investigated in different branches (e.g. automotive, aircraft and naval architecture) in order to derive a set of standard parametric working surfaces. The long-term objective of this research topic will be the integration of the described concept as a standard feature in 3D-CAD-Systems.

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