3D Sketching in VR Changing PDM Processes

Carsten Seybold, Frank Mantwill

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Carsten Seybold* and Frank Mantwill

Helmut-Schmidt-University, Holstenhofweg 85, 22043 Hamburg, Germany
carsten.seybold@hsu-hh.de* , frank.mantwill@hsu-hh.de
*Corresponding Author

Abstract. The use of PDM systems is especially in the late phases of product development state of the art. In fact, it is possible to integrate requirements for future products in the meaning of product lifecycle management into a PDM system. The following steps of product development like initial design sketches are almost not represented yet. Early design work is currently done without computer assistance. An integration of handcrafted sketches in PDM systems is in the case of digitalization possible, but further use is strongly limited. Concluding, in the early phases of product development a gap does still exist in computer assistance. 3D sketching in Virtual Reality (VR) helps to close this gap. Certainly, PDM systems are not prepared for integrating such content in present structures and processes. An approach to integrate these sketches into PDM systems is the main key to establish 3D sketches in product development. To evaluate the use of 3D sketches, a demonstrator in VR has been developed. 27 test subjects worked on two different tasks within this tool. An analysis of the working process and the created solutions shows that sketching in VR could be a possible assistance. In order to cater to these results, a process to handle sketches in PDM has been developed. This process allows preparing sketches with further information and preparing them for further use. The objective is to reach a traceability for the product from requirements via sketches to CAD models to complete the product lifecycle management approach in companies.

Keywords: PDM, VR, Sketching, concept life cycle, product development, design.

1 The Early Phases of Product Design

Product development is already been strongly affected by computer support for several years. Without computer support, many of the working methods used in product development are not possible [1]. Database systems, such as product data management (PDM) systems, provide continuous support to the product development process through all phases. However, the situation for support through concrete work applications is different. In the late phases, Computer Aided design (CAD) and other CAx-systems up to digital factory support design with dedicated applications. In the early phases, work steps are realized with office applications or even manually without digital support. As a result, the support possibilities of PDM systems cannot be used sufficiently in the early phases of product development. While requirements for products can be easily digitized and mapped in PDM systems, problems arise with hand-drawn sketches, handwritten notes or even physical models made of cardboard or something else. Sketches and notes can indeed be digitized and stored in PDM. Further use of scanned documents is severely restricted by the few interaction possibilities. A model-based approach is the Sketch Port Model in Systems Engineering. The objective is to provide the product designer with a methodology that combines abstract functional models and 3D CAD models [2]. However, this approach focuses on the interface between the systems engineer and the product designer of the mechanical components.

In order to bypass this media break in PDM, the approach pursued is to develop a concept lifecycle that allows consistency in the development process within the PDM system in conjunction with 3D sketches from virtual reality environments. 3D sketches, annotations and further information can be integrated into PDM systems in a use-oriented way and build up a basis for the detailing in CAD. Figure 1 shows the current computer support in the product development process and the solution pursued here.

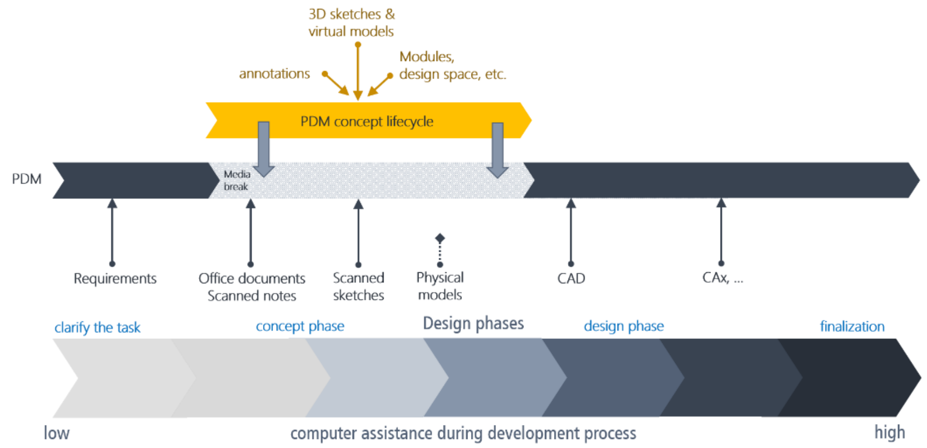

Fig. 1. Computer support in the product development process and the concept lifecycle approach

2 Sketches as External Support and the Connection to CAD and VR

However, why are sketches so important that further use in PDM systems is an objective? Sketches support intellectual activity [3]. They are used as analysis-, solution-, communication- and documentation support. In a few cases, they are also used as an assessment support, but typically here are other form of support used [4]. In addition, sketching has been proven to accelerate the work in product design [3]. In the past, the subsequent digitization of sketches created by hand and further processing has hardly been used [5]. Therefore, a change and support by digital tools seems to make sense. Proven CAD systems could offer a solution here. Among other things, CAD systems are suitable systems for visualization and communication - functions that are also very relevant for sketches [6]. In their use, CAD systems require the input of exact parameters, such as length dimensions or position conditions. However, sketches are deliberately kept imprecise. Individual sketched lines get not too much importance and there is space for change [7]. Therefore, common CAD software supports the early phases of product development not in a meaningful way [8]. In fact, it is not advised to use CAD-Systems in the early phases [6]. In addition, the use of CAD can even have a negative impact on creativity [7].

A platform for 3D sketching tools can be offered by virtual reality, or VR for short. The most common definition is formed by the three I, interaction, immersion and imagination. The user of virtual reality has the possibility to influence or change the virtual world (interaction). By appealing to the user's senses, the user is immersed in the environment (immersion) and how well the virtual environment works depends largely on the user's imagination [9]. A high level of immersion and imagination in virtual environments can only be achieved by a real-time capability of these environments [10]. Head Mounted Displays (HMD’s) and CAVE systems (a projection based VR area) are regarded as such immersive VR systems [11]. The use of CAD or other CAx systems represent a special kind of virtual reality, called non-immersive virtual techniques. As a difference to non-immersive virtual techniques VR allow to display and interact with objects in a realistic environment and on a 1:1 scale. This is possible with the currently common HMD systems via stereoscopic immersion and intuitive interaction modalities. The interaction modalities in VR will allow a fast but relatively rough interaction. Working with high precision as in CAD is not intended in VR.

3 The Use of VR in Product Development

Looking at the literature published on VR in recent years, numerous use cases for VR in the product development process can be found:

- Design-Review processes [12,11],
- Evaluation of design alternatives [14,15],
- Realistic representation of vehicles without physical prototypes [16],
- Product presentation in the customer environment [16],
- Marketing [13],
- Visibility studies [12],
- Ergonomics studies [12,15],
- DMU collision checks and assembly simulations [15],
- Assembly and installation studies [14,15],
- Visualizations of FEM and CFD calculations [15],
- Wiring simulations [12],
- Studies on the virtual prototype [14],
- Testing of products for acceptance [15],
- Comparison of variants [15],
- Education and training [13,17],
- Service measures (validation of work steps), tele maintenance (AR) [11].

In addition, research also include applications of VR in the field of communication [13] [18]. It is obvious that the VR technology is already used in various fields in product development. On a closer look at the use cases, it is clear that they partly overlap or cover very similar areas. In fact, VR is being used more and more in individual sectors such as the automotive industry - but these are individual applications. A comprehensive or even cross-industry use has not yet taken place. This applies to the area of product development, but also to the area of production or the digital factory, where very similar fields of application can be found [19].

It is also obvious that the applications are limited to the presentation and evaluation of mainly visual product properties [20]. Use cases such as the education of maintenance personnel, assembly simulations or training are used for simulations that are usually created outside VR in advance. Up to now, the industry uses Virtual Reality not to create new content. It is evident that the visualization of product functions in VR is most highly valued by companies. The support for communication is also gaining importance [10]. It is therefore appropriate to assume that VR will continue to increase its importance, especially in these areas.

However, VR technology has developed strongly in recent years, especially in the area of hardware. While for example in the automotive industry expensive CAVE systems are still often used for design review, low cost VR systems like HMD's are now available for the consumer and also for professional applications. In addition to the actual HMD viewing system, the most common systems have intuitive control units, which allow the VR user to interact with his environment and not only change the viewing angle. The low-cost hardware, development platforms from the gaming industry and the possibility of interacting more with virtual environments have reduced the barriers for the use of this technology in recent years.

It must be assumed that VR will spread further into other fields of application. Bruns (2015) even assesses VR as a key technology. The use of VR can offer opportunities for companies, such as competitive advantages. Risks resulting from high investments must also be taken into account. In fact, the significance of the opportunities offered by this technology is becoming increasingly secondary. The risk that arises from disregarding this key technology is increasing and companies must consider whether they can continue to disclaim VR technology [13]. To achieve a benefit the use of VR require certain conditions. The exchange of data between CAD and VR systems is still a problem [14]. Up to now, CAD models cannot be used in VR without further adaptations. In most cases, in addition to conversions, strong simplifications are necessary to achieve real-time capability for the geometric data. The future of VR requires a better integration of CAD, VR and also PDM. The connection of VR to PDM systems is getting an increasingly important role [14].

The same applies to VR support in the early phases of product development. If VR is used to provide an environment in which the product designer is supported in finding solutions by creating 3D sketches and models, it cannot be considered as a stand-alone software solution. In order to achieve a consistent digital product development, a connection to the PDM system must be established [14].

4 VR-Sketching as a New Approach

In order to investigate the support of the product development process during sketching, the Helmut Schmidt University (HSU) developed a demonstrator. Similar approaches are also available like SketchAR [21], Lift-Off [22], Napkin Sketch [23] and others. However, these methods focus on other problems, such as styling [21], transferring existing hand sketches into 3D [22] or projective 3D sketching [23]. For the demonstrator at HSU is the focus on providing a tool that support the product designer in finding and selecting alternative solutions and establishing a basis for further work in CAD. The hardware of the demonstrator is a common HMD, the Vive from HTC. In addition to the tracking of HMD and two control elements, it also allow a comparatively large movement area of $12m^2$. The software is created in the development environment Unity and provides the user with functions for sketching and modelling. These are for example, freehand sketching, drawing straight lines and circular arcs and sketching options such as changing the line width, color and line shape. The demonstrator provide also geometric basic bodies for modelling according to a modular system. In addition, the user can position, copy, group and manipulate objects freely in the virtual environment. Measuring distance and inserting audio comments are further supporting tools. These and other functions are available to the user in the form of a selection menu directly on one of the control elements, so that the user can select the function with the other control element and following use it in the virtual environment. In addition to the internal possibility to save and load work progress, it is also possible to export that work process as a .stl file. Further use in CAD is thus possible.

In order to determine the benefits of a VR sketching tool, such as the demonstrator developed at the HSU, two different design problems are developed, which were worked on by a total of 27 test subjects. The first task is to design an engine test bed. This test bed should be able to place and operate a car engine including all necessary attachments and further requirements have to be considered. In addition to this constructive task, the focus at the second task is placed on facility planning and workplace design. Here is the objective to redesign an area of test bench installations. In addition to the positioning of the test benches and the associated valve and pump units, the location of hydraulic tubes, escape routes and accessibility by crane also needed to be considered.

The tasks for the test subjects have their origin in real cases and they are oriented in the structure as closely as possible to the real working methods and the working environment of product designers and system planners. The test subjects had to finalize and prioritize the requirements based on the given information. It was also important that the test subjects required no special expertise in finding a solution. Otherwise, the task provided the necessary information or the problem was simplified. In addition, the objective was not to design a finished solution detailed in CAD, but a concept solution. The test subject should therefore create a design sketch or a design model, which enables further work and detailing in CAD. An example of creating a sketch in the VR demonstrator is shown in figure 2.

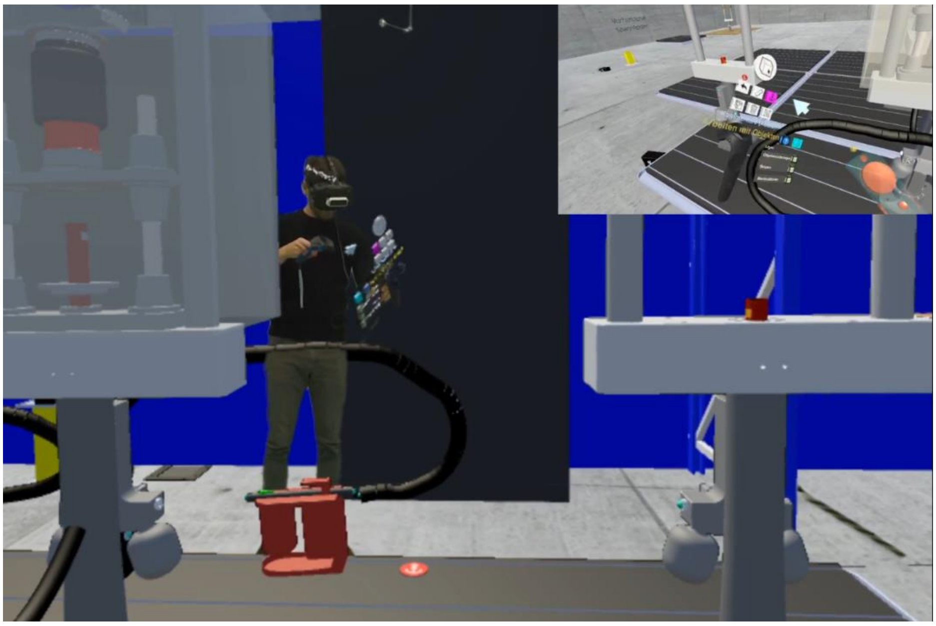

Fig. 2. Mixed reality view of a test subject during the solving of the task *test bed installation*, including the view of the test subject in the top right corner

Fifteen test subjects processed task 1 in VR, twelve test subjects processed task 2. The test subjects represented different ages. Eleven subjects have been 24 up to 29 years, 14 test subjects were at the age of 30 - 40 years. Two test subjects were significantly older with 46 and 59 years of age. The spectrum of professional experience is wide. Some of them had a professional experience of 10 to 19 years (3 subjects), but many were still students in technical master's degree courses without significant professional experience (11 subjects). In addition, there are different career paths, including a chief engineer and also design engineers and technical product designers without academic graduate (3 subjects). On the other hand, there is a conventionally created comparative solution for each task. The independent comparative test subject is at the age of 57 and is skilled with 30 years of professional experience as a designer. While creating the solution, the test subject used several hand-drawn sketches to visualize the solution and a CAD system to preposition given components in space.

A comprehensive evaluation of the test results is still pending. However, it is for example certain that the processing time of the task "engine test bed" in the VR sketching environment took averagely only 35.4% of the time compared to the conventionally created comparative solution. The average quality of the solutions remained the same. A more detailed chart is shown in Figure 3. In addition, the comparative test subject could not represent safety aspects such as concrete protective devices and hose line routing like cooling and fuel in his manual sketches. These aspects are only considered in the later CAD detailing. In contrast the VR test subjects represented these aspects. An evaluation of the solutions created by the test subjects showed, that solutions created in VR get a higher ranking as hand-written sketches in aspects like the further usability.

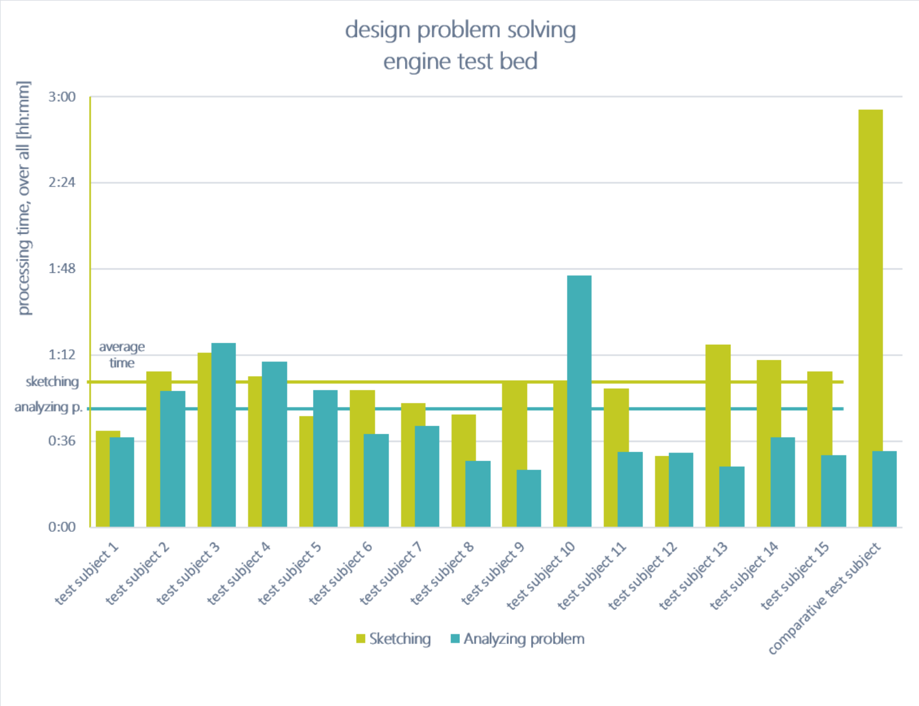

Fig. 3. Results test subjects for the problem "engine test bed" during the 3D sketch creation

In summary, 3D sketches and models are portable to VR and this technology has the potential to support the product development process in a medium or long term - even if 3D sketching should only complement the hand-drawn sketches and not completely replace it. But how should this new generation of data be integrated into the structure of product data management systems with the most possible benefit? PDM systems are not yet prepared for this. Although it is possible to store this kind of data resulting from the sketches easily, for example by assigning it to a project, to CAD data objects or as a separate independent data object. A process related assignment is not yet possible. This applies especially to 3D sketches created with the use of VR tools, but it is also valid for hand-drawn sketches. An assignment in PDM has to be found that is effective for all kinds of sketches.

5 Current Data Storage in PDM Systems

The functionality and the range of functions of PDM systems vary depending on the manufacturer. The implementation in companies is also individually different and adapted to the needs of the company [24]. Despite numerous differences and individualization options, PDM systems always follow the same approaches in their core functions. CAD data are stored as separate objects in the system, consisting of the actual CAD files and associated metadata. CAD objects pass a fixed status network, the object lifecycle, shown in its basic form in Figure 4 [24]. Such lifecycle has proven itself and ensures that changes to CAD objects, which are located in the status "approved", are no longer possible. A defined status can be committed to production. If changes are necessary, it is only possible to deviate a new version of the CAD object [24]. Each relevant CAD component and each CAD assembly of a product is stored in the system as a CAD object and each object passes through individual states. This ensures that the processing advance of each component and each assembly can be read out directly. To assign CAD objects to a context, there are mostly project and product structures in PDM systems available. Accompanying documents can be displayed as attachments to CAD objects, as a separate object class assigned to a project or product structure, or linked to CAD objects. The same applies to requirements, which could also be mapped. This can be done as metadata in a project structure or as a separate object class. If requirements are created as a separate object, a link between projects and CAD objects is possible.

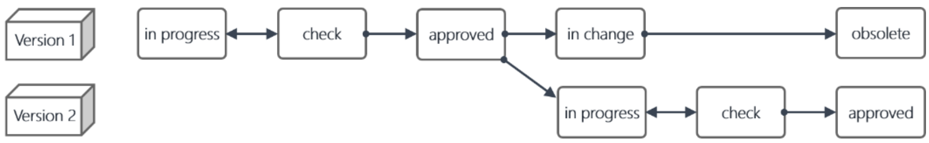

Fig. 4. Standard Object Lifecycle for CAD objects in PDM systems, based on [24]

It would be conceivable to store 3D sketches according to the same scheme in PDM systems: As a separate object class with a lifecycle based on the standard object lifecycle "concept creation - check - approved for CAD". Such a procedure is already used for technical drawings. The work on these drawings is located towards the work on CAD models. Of course, a CAD model does not have to be completely finished to start the work on the technical drawings. However, technical drawings are only released after the associated CAD models have been released. The prevention of further changes is an immediate requirement for production. Sketches, on the other hand, are a tool, an external form of support. Sketches are not a requirement for working in CAD or further steps in the product development process. In addition, fully complete sketches will not be reachable. Due to the fact that sketches rely on a lack of definition and simplifying aspects, complete sketches are neither possible nor intended favored.

6 The Status Network of Concept Models According to a Maturity Level Principle

How can the lifecycle of sketches be mapped in PDM systems if sketches cannot be fully CAD approved? One solution could be the status network developed below. After a initial status a flexible arrangement of further statuses follows. It is possible to switch from status to status as required. The steps do not have to be executed in a prescribed sequence. The product designer has the possibility to skip work steps and complete them later in the problem solving process. The status network is shown in Figure 5.

The initial status "concept design" is taken directly when a sketch object is created in PDM. In this state, the 3D sketch and the relevant metadata must be created in the system. If there are several sketches of the same object, the product designer can also assign them to the same sketch object. Further 3D sketches of subassemblies or constructive details can be created as a separate sketch object below the main sketch structure with the possibility to transfer them to a later CAD structure. In this way, initial structural relationships can already be represented. The status and activity content in the middle section of the status network is structured as follows:

- Modularization (modular design): In this status, the product designer defines the future modules and therefore large parts of the future assembly structure. In the simplest case, this can be the entry of structural relationships in the metadata of the sketch object. Alternatively, the assignment of geometry elements of the sketches within a PDM-internal viewer or directly from VR to specific modules is possible. The objective is an automatic extraction of a product structure for further processing in CAD when work in CAD begins.
- Requirement assignment & verification (requirement mapping): If the product designer chooses this status, he gets the possibility to link geometric elements, modules (if already defined) or module sections with requirements for the product. This assignment can be done in VR or in a PDM-internal viewer, similar to common redlining functions. Of course, to do this, requirements must be represented in the project or product context in the PDM system. In addition, it would be conceivable to record new requirements in this status, which only arise after selecting a principle solution and during creating the sketch and are not based on the initial situation. It is only possible to assign requirements if they have a geometric reference, which is not necessarily the case for all requirements. According to this, the existing requirements must be categorized. Later on, it is possible to link the further CAD models with the sketches and requirements. If certain sketch elements are not in line with the requirements, it can be noted accordingly and alternatives can be designed.
- Individualization check (clarification): The product designer must decide during his work whether individual components must be designed and manufactured as house parts in the company or whether purchased parts should be used. In this status, the objective is to prepare, evaluate and select several alternative solutions for these components if necessary. Information of selected alternatives can be directly reused for CAD, but also the information of the approaches not pursued further is retained and can therefore be reused later if necessary.

It is obvious that the intermediate statuses in concept lifecycle do not exclusively deal with sketch editing. Rather, the sketches are enriched with additional information to facilitate the change to the detailing phase in CAD. The status network is supported by a percentage maturity level, which is assigned to the sketch object, i.e. to the 3D sketch with its meta-information. This level of maturity should enable an evaluation of how much a 3D sketch with its metadata is suitable for further processing in CAD. This avoids a rigid status change to "approved for CAD" and therefore a rigid boundary between "suitable" and "unsuitable". Ideally, the product designer achieves a high level of maturity by completing and fulfilling the previous work steps before starting work in CAD. However, it is also possible for the product designer to start early in CAD. In this case, he will be made aware of the work steps that are still open. As shown in Figure 5, the maturity level of the concept model can be carried out across all lifecycle elements on a percentage basis. This means that subordinate sketch entities, such as detailed sketches of individual areas or sketches of subassemblies, influence the overall maturity level. In addition to a percentage calculation, other simplified representations of the maturity level are also possible, for example, using the Likert scale or a traffic light system.

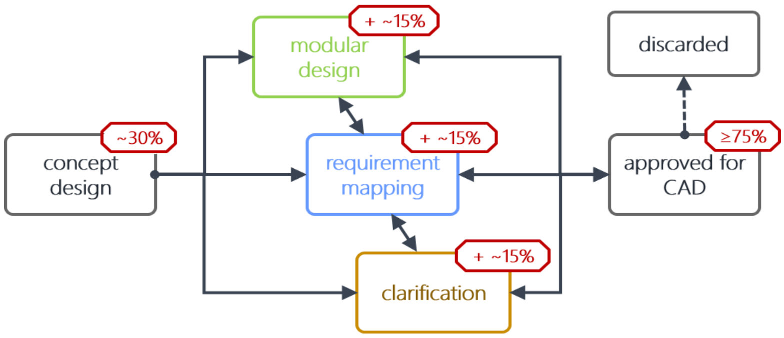

Fig. 5. Object Lifecycle for concept models in PDM systems

Whenever the product designer is not working on one of the task packages of the intermediate work steps, the final status “approved for CAD” is taken. If a sketch is not in line with the requirements, it is also possible to change it to status "discarded" and, if necessary, upload a new sketch as a new version into the PDM system. A discarded sketch is no longer included in the maturity level calculation.

A possible procedure could look like the following: A product designer creates a 3D sketch for a new product "Test Bench for car engines" in VR and uploads it into the PDM system. The sketch object receives the status "concept design" and for example a initial maturity level of 25%. The product designer assigns in the status "modular design" a module to certain sketch elements in VR based on the initial thoughts during sketch creation. In the PDM, the assigned modules are hierarchically organized. Afterwards the product designer switches to the "requirement mapping" status to link the requirement "Mobility of the Test Bench" to the wheels in the sketch. This assignment could be done in a viewer integrated in the PDM system. Hereafter, the product designer assigns further requirements. During a break, the sketch object remains in the “approved for CAD” status. Therefore, the maturity level has increased due to the previous editing of the requirements. In a further processing step, the product designer decides to purchase the wheels and other components of the future test bench and not to manufacture them. These decisions are entered into the sketch object in the status "clarification". In this example, the concept model has now reached a maturity level of 68% as a result of processing. The product designer decides to transfer the structure created in the "modular design" step to a CAD object structure and to start working in CAD.

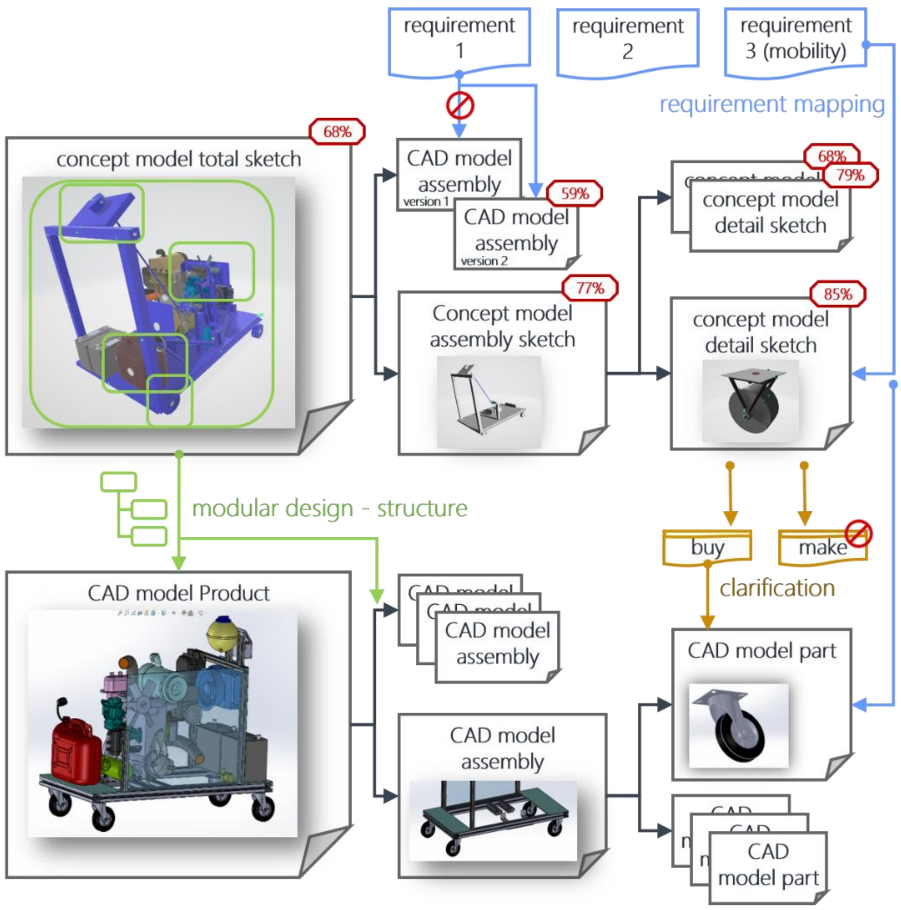

Fig. 6. Example of a concept model with selected functions within the PDM structure

This example shows what editing of the concept models might look like in future with the concept lifecycle. Throughout the process, the product designer can edit and complete metadata of the sketch object and makes changes or additions to the sketch as needed. However, if the product designer makes changes to the sketch, the system will create a new version of the sketch automatically. This ensures that older versions of the sketch can always be accessed. The relationships between the individual states and their effects on the concept model are shown in an example in Figure 6.

7 Achievable Objectives with 3D Sketches and the Concept Lifecycle

With the implementation of such a concept model, the product designer has to deal with a corresponding amount of effort in the daily application in his work. This effort must be offset by a corresponding benefit. The use of 3D sketches and their integration into PDM systems generally provide a better possibility for further use in CAD detailing as handwritten sketches. 3D sketches are already available in a stereoscopic view, so there is no need to derive the 3D geometry from different views like in handwritten sketches. For the drawing of perspective representations, the product designer needs knowledge about the creation of projections in the area of hand sketches. This is not necessary when creating sketches directly in 3D [25]. In addition, the 3D sketch can be opened directly in CAD and used as a semi-transparent template. Proportions and positioning can partly be transferred directly. This means that the product designer can expect a quicker procedure in the area of initial geometry creation in CAD. It is also possible to create sketches or parts of sketches by non-developers in the future, which can then be further processed by the product designer.

The concept lifecycle model is most effective for 3D-sketches, especially in linking geometry and further information like requirements or modules. However, it is also suitable for hand written sketches. Typical operations in companies can be supported without the capital investment into VR technology. It is obvious that the model of a concept lifecycle does not support mainly the sketching itself. The concept lifecycle is styled to enrich the sketches with further information to support the following work in CAD. With the concept lifecycle, it is possible to archive consistency from the requirement via the sketch to the finished CAD component. This also applies to concept ideas that are not pursued further or are not in line to the requirements. Continuity is particularly important in industries where exact traceability is required. This can be extended with this approach. In principle, the concept model can be a useful addition. This applies to the development of new model series, subsequent products or to designs adapted to new requirements. Here, it is possible to fall back on sketches of the previous design, so that the product designer can reuse them. The reuse of partial solutions, which the company has already generated, saves time and effort. The concept model encourages the product designer to take a closer look at certain stages of product development after the sketches have been created. Especially inexperienced product designers are instructed so that important aspects are not left out. By guiding the product designer through the systematics of the product development methodology, problems or errors in the design implementation of the product can be identified and eliminated at an early stage, which is a main objective according to the "rule of ten" of error elimination costs [24].

8 Summary and Outlook

This paper has shown, that there is still a gap existing in computer assistance during product development. PDM systems could support all phases of product development, if sketches can be integrated in a beneficial way. The approach applied here was to close this gap by the use of 3D sketches in VR. During a study, test subjects solved two different design tasks with the use of a VR tool. Afterwards the designed solutions and the work itself have been rated. The result of the evaluation is that 3D sketching in VR has a positive influence on product development. The advantages are a comparatively fast creation and easier reusability as hand-drawn sketches. For the efficient and further use of 3D sketches, an integration of 3D sketches into the PDM-supported development processes is required. One solution can be the approach presented here, a concept lifecycle model for 3D sketches within PDM systems. This concept lifecycle model is not based on a rigid status network. It depends on a maturity level system to achieve the necessary level of flexibility. The concept lifecycle model achieves a consistency from the requirements to the sketches and up to the CAD models. This concept lifecycle model supports common hand-drawn sketches but also digital 3D sketches with benefits in linking objects. In addition, the model supports the product designer in the further processing of sketches and prepares for the next steps in the product design process. Further research is needed to analyze how the concept model can be extended to cover previous steps in the product development process and a cross-departmental approach in systems engineering. Subsequently, the optimized concept model is to be validated in a realistic application.

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