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A NEW "KNOWLEDGE-BASED ENGINEERING" GUIDELINE

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Abstract

It is necessary to enable product developers to use specific engineering knowledge in an efficient and fast way during the product development process. However, existing procedures supporting the development of products are not strictly convenient to meet this challenge. This is the reason why already in the 1980 various research approaches in the area of knowledge-based engineering (KBE) have been developed. Nevertheless, there is still no uniform and universally applicable description for the industrial environment, with which a KBE application can be implemented and operated. Therefore, the aim is empowering designers to use design-related knowledge in CAD-systems as a central engineering workbench. The main research question in this paper is: How to formulate a universally applicable procedure to conduct KBE-projects with all relevant roles as well as necessary instructions and recommendations regarding specific KBE-methods and -tools? By answering this question, this contribution offers insights in general adapted definitions and perspectives, a procedure for the implementation of KBE-projects, a classification of knowledge-based engineering and a first exemplary solution.

Keywords: Computer Aided Design (CAD), Computational design methods, Design informatics, Knowledge management, Product modelling

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1 PROBLEM DESCRIPTION AND MOTIVATION

Product developers and designers are nowadays confronted with a wide variety of challenges in their daily work. There is a remarkable change in society and markets. Whereas in the past, work or capital has been the major bottlenecks in value-added processes, knowledge can be seen by now as an essential resource (Bürgel and Zeller, 1998). Thus, the task is to ensure that knowledge can be used in a most efficient way, affected by e.g. progressive globalisation of markets, rising pressure to innovate or as well a high level of individuality in the international sales regions. Focusing on the domain of engineering and knowledge, it is necessary to enable designers using the product or situation specific knowledge (Luft et al., 2013). However, existing processes supporting the development of products are not strictly convenient to meet this challenge. This is the reason why already in the 1980 various research approaches in the area of Knowledge Based Engineering – in short KBE – have been developed. Though, there is still no uniform and universally applicable description for the industrial environment, with which a KBE application can be implemented and operated.

2 AIM OF THIS CONTRIBUTION

Referring to the problem description and motivation, it is the aim of this contribution to close the aforementioned gap and to offer guidance, empowering designers to use design-related knowledge in CAD-systems as a central engineering workbench. For this purpose, it is necessary to regard topics as gathering data, formalizing and as well integrating knowledge. The results will be published completely in the VDI-guideline VDI5610 Sheet 2.

The main research question to be answered can be stated as follows: *How to formulate a universally applicable procedure to conduct KBE-projects with all relevant roles as well as necessary instructions and recommendations regarding specific KBE-methods and -tools?*

This superior question comprises thereby considerations about e.g. what is KBE, where can it be applied (or not), why do we need “it”, what types of KBE application are there, what is the right application for the present problem and how can an introductory scenario be formulated, what IT-tools are necessary, what boundary conditions have to be fulfilled in the company, what resources should be provided and further aspects.

By answering the main research question and keeping those exemplarily questions in mind, this contribution offers first insights in general adapted definitions and perspectives, a procedure for the implementation of KBE-projects, a classification of knowledge-based designing and a first exemplarily solution example.

3 PRINCIPLES OF THE KNOWLEDGE-BASED DESIGN

In the following, adopted definitions and general perspectives are presented in order to improve the understanding of the subsequent chapters. First, the differentiation of the two terms designing and configuration is important. Designing includes all work steps in order to clearly describe and represent technical artefacts (e.g. individual components, subassemblies, systems), which exist in the designer´s mind (Conrad, 2008). In contrast, configuration - which is often equated with product configurators - primarily aims for the composition of a product based on standardised components and tested configuration rules (Conrad, 2008).

In literature, there are many terms and definitions concerning the terms, structural types, classification etc. regarding knowledge. The VDI guideline 5610 Sheet 1is based on the differentiation according to (Roth et al., 2010). Herein, **knowledge** is described by the five structural parameters *knowledge type* (e.g. method knowledge), *knowledge characteristics* (e.g. implicit or explicit), *knowledge form* (e.g. figure, rule*), knowledge location* (e.g. database) and *knowledge quality* (e.g. traceability).

Domain-specific knowledge for problem solving has to be formalized from different knowledge sources. Therefore, the often implicitly existing knowledge has to be transferred to an explicit knowledge representation form. This process is called **acquisition of knowledge** and includes the two phases *knowledge collection* as well as *knowledge interpretation* (Wartzack, 2001). Finally, the knowledge implementation follows this whole process (Spur and Krause, 1997; Wartzack, 2001; Puppe, 1991; Arbeitspapiere der GMD 338, 1988; Borndorff-Eccarius, 1998).

The knowledge collection serves for extracting and gathering knowledge from various knowledge types and locations. During the subsequent knowledge interpretation phase, the collected knowledge is analysed, structured and transferred to a formal universally applicable model for the problem solving process of the relevant KBE application. In literature (cf. Spur and Krause, 1997; Wartzack, 2001; Puppe, 1991; Arbeitspapiere der GMD 338, 1988; Borndorff-Eccarius, 1998), the following tree types of knowledge acquisition are differentiated (see Figure 1):

- **Indirect knowledge acquisition:** As human knowledge and gained experiences are often difficult to retrieve and formulate, the knowledge engineer has to extract the expert´s knowledge (Luft et al., 2013)(e.g. through interviews, questionnaires or observation). Subsequently, the knowledge has to be represented in a computer-processable form. It is essential for this type of knowledge acquisition that the knowledge engineer is familiar with the expert´s knowledge domain as he has to internalize the expert´s thought process and procedure.
- **Direct knowledge acquisition:** Within this method, the expert directly communicates with an "intelligent" acquisition tool of the system. Communication problems between the knowledge engineer and the expert can be eliminated, as the expert defines his expertise autonomously, fills the knowledge base and evaluates the system´s behaviour. The acquisition tool then transfers the expert´s knowledge into an appropriate knowledge representation (Spur and Krause, 1997; Puppe, 1991). Generally, the direct knowledge acquisition is most suitable for system maintenance and for the expansion of the knowledge base instead of its creation (Küstner et al., 2015).
- **Automatic knowledge acquisition:** The automatic knowledge acquisition transfers text-based knowledge into knowledge that can be processed by a computer and extracts knowledge from case examples, respectively without the expert´s or knowledge engineer´s intervention. The terms "Knowledge Discovery in Databased" (KDD) or "Data Mining" summarizes the methods of automatic knowledge acquisition, which can be used for different application fields.

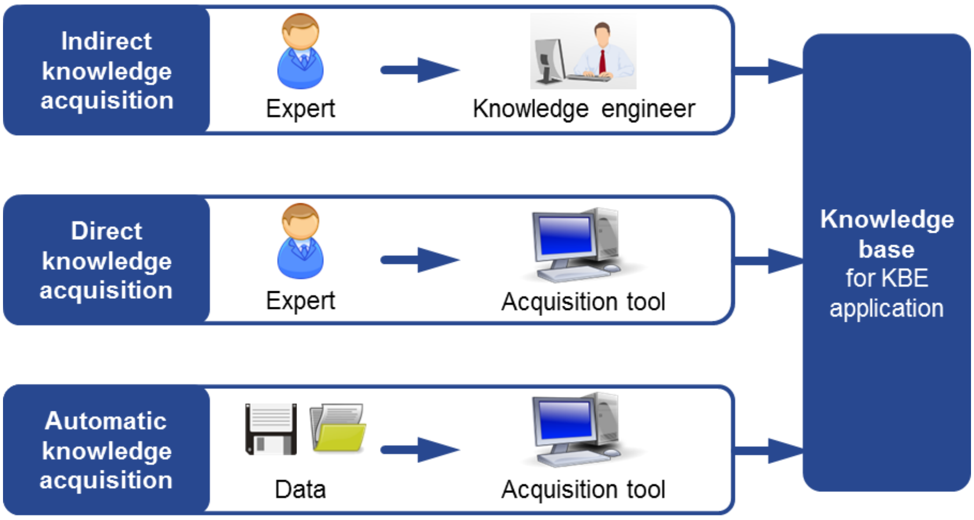

Figure 1. Three different types of knowledge acquisition

Within KBE applications, different typical forms of representation are available. They can be differed into the two groups "declarative" and "procedural" knowledge representation. Declarative knowledge representation concentrates on the description of facts and disregards the concrete knowledge application, whereas the procedural knowledge representation emphasizes it. Therefore, the second method represents a relatively application-oriented type of knowledge representation and completes the declarative knowledge representation (Kurbel, 1992).

The step of knowledge representation consists of the partial steps *knowledge analyses* and *knowledge structuring*. It describes a host of syntactic (rules of arrangement) and semantic (rules of meaning) specifications for the description of things and factual circumstances. The following three representation types are relevant for the knowledge-based and computer-assisted design (Puppe, 1991; Görz et al., 2003; Blumauer and Pelligrini, 2006; Rude, 1998):

- **Rules** or production rules consist of a condition part and an action part. As there is an analogy to the human way of thinking and problem solving, experts are easily able to express their knowledge in the form of rules.

- **Constraints** describe a mathematical relation between different variables (e.g. U= R*I) and are differentiated into geometric and engineering constraints.
- **Frames** are formally understood as an analogy to the "long proven" filing cabinet system which suits for representing repeating objects (e.g. components, subassemblies).

4 PROCEDURE FOR THE IMPLEMENTATION OF KBE PROJECTS

For the pragmatic implementation of a KBE-project, a systematic and general procedure is indispensable (cf. VDI 5610). Thus, such a procedure has been developed within the VDI technical committee 111 and can be seen in Figure 2. It becomes clear that a KBE-project can be divided into the four phases - planning, development, test and operation - which will be described in Section 3.2. For the execution of the tasks within the individual phases, different roles are defined. Because of this "thinking in roles", one person can own several roles (Luft et al., 2012). Thereby, already existing roles should not be replaced by the roles of a KBE-project but further KBE-specific tasks can be assigned to these roles. The following subchapters provide a clearer understanding of roles, the cross-sectional topic "Security and knowledge protection" and the four project phases.

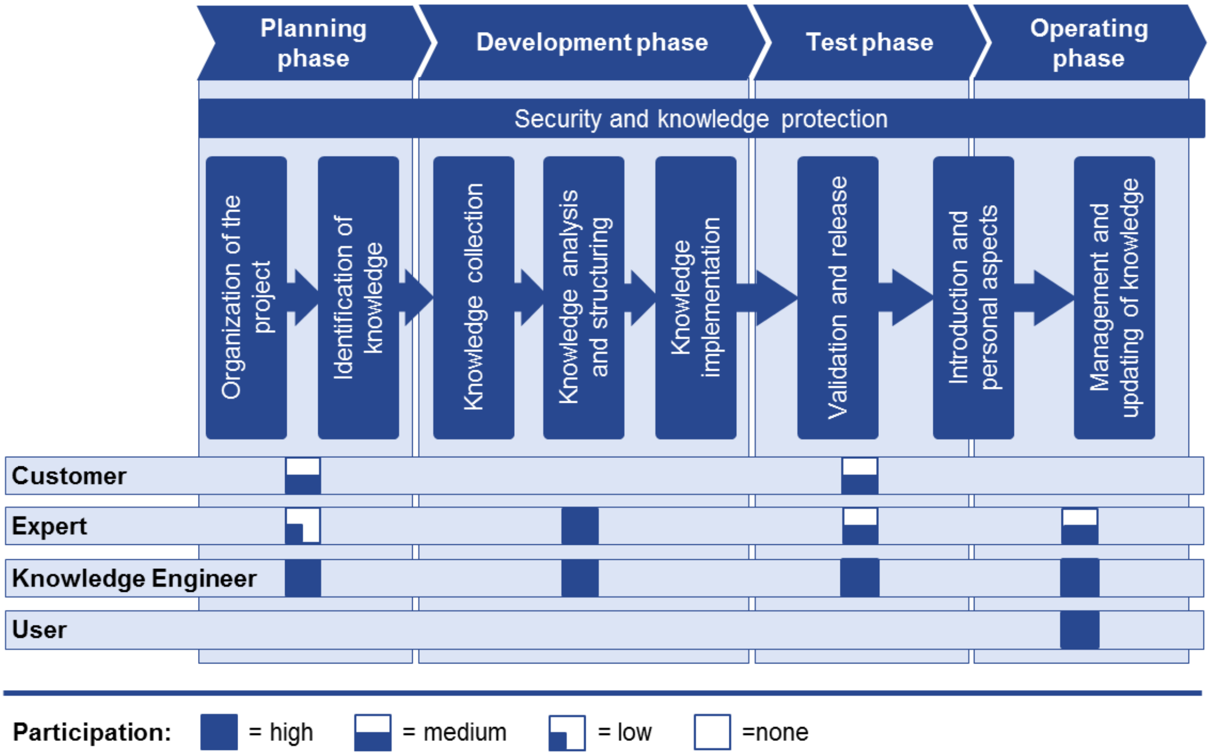

Figure 2. Overall procedure of a KBE-project (cf. also Luft et al., 2012)

4.1 Roles in a KBE-Project

For the implementation of a KBE-project, different competences and responsibilities are necessary. Typical roles are the customer, expert, user and the knowledge engineer, whereas the last one has the highest participation and therefore holds an important position (cf. Figure 2). In the following sections, the four roles are outlined.

4.1.1 Customer

Due to the potential benefits of the knowledge-based engineering, the customer is responsible for the initialisation of a KBE project (e.g. knowledge-based construction of a shaft-hub-connection). At the beginning of the planning phase he defines the aim of the project (e.g. type and scope of the KBE application) and allocates employees to the project who own the necessary qualifications. As the knowledge engineer undertakes the task of managing the project, the customer assumes a subordinate function in the further process. He is just involved in the validation of the KBE application and the verification of the target achievement in the test phase.

4.1.2 Expert

The expert (e.g. designer, production planner) participates in all phases. In the planning and especially the development phase he is active within the acquisition of the relevant knowledge. As well as the customer, the expert contributes to the validation of the KBE application in the test phase (e.g. by specification of a text case). Finally, in the operation phase he assists the knowledge engineer in improving the KBE application, for example in the continuous extension of the knowledge base.

4.1.3 User

By using the KBE systems, the user especially is involved in the operation phase to reach a certain design or layout objective. However, it is important to consider the potential users´ wishes already in the planning and the development phase. Moreover, the user – which is often the designer himself –has to be integrated in the test phase to utilize his experience in working with the company-internal CAD system.

4.1.4 Knowledge engineer

As already mentioned, the knowledge engineer plays the most important role in the KBE project because he is strongly involved over the entire life cycle of the KBE application. Thereby, this role has an important mediating role while forming a bridge between the strategic objectives of the company management or the knowledge managers and the users working operatively on the business process (Luft et al., 2012). Another task – next to the whole planning, development and operating process of a knowledge-based system – is to gather the human expert knowledge by using suitable methods. Afterwards it has to be incorporated in a KBE application (Karbach and Linster, 1990; Bimazubute, 2005). To successfully manage the tasks of motivating the employees, arbitrate between different interest groups and eliminate knowledge management barriers (e.g. rationalisation fears), the knowledge engineer needs – amongst others - a broad and fundamental range of engineering knowledge as well as a solid knowledge of information and communication sciences (Luft et al., 2012).
As KBE projects are often performed with external support (e.g. service provider for the implementation of KBE applications), the role of the knowledge engineer can be assumed by employees outside the company in this case.

4.2 Conceptual Description of the procedure steps

In this section, the four essential phases within the implementation of a KBE-project are outlined in summary. Finally, the topic *security and knowledge protection* will be explained (compare to guideline VDI 5610 for a detailed description).

4.2.1 Planning

First of all, the KBE project will be projected and prepared according to the defined requirements in the planning phase. The approach CommonKADS (Schreiber and Akkermans, 2002) is well suited for knowledge based systems.
The first step includes the KBE-project´s implementation in the company organization and the identification of the relevant knowledge. Therefore, it is necessary to analyse business processes and knowledge carriers, carry out a target-performance comparison and identify involved employees and resources. For supporting the already mentioned tasks, a concrete framework – the organisation model – is provided which consists of five steps (OM1-OM5) (Schreiber and Akkermans, 2002).
The first step determines the different roles by means of a *problem description* (OM1). Subsequently, the problems are identified within the organisation and potential solutions are determined. The management then takes the decision whether the KBE application will be developed. In a next step, the visual *description of the relevant business process* (OM2) takes place. Within a *detailed process description* (OM3), the process is detailed apart from individual, e.g. knowledge intensive, tasks. The *description of the knowledge base* (OM4) is very important for analysing the knowledge base in the following and is part of the fourth step. It is therefore necessary to identify knowledge bases and allocate them to a knowledge carrier (e.g. employee or IT system). Furthermore, checking the correctness of the knowledge base or elements is of great significance. If the knowledge does not have the required type or is not available at the right place, to the right time and at the right quality, it has to be adjusted. Finally, the fifth step includes the *formulation of a feasibility analysis* (OM5). Therefore, a decision document

for the customer of the KBE project is prepared and provided. This document thus supports the management in making a decision regarding the future development of the KBE system.

4.2.2 Development

The following development phase is divided into the three sections knowledge collection, knowledge analysis and structuring and knowledge implementation. Within the knowledge collection, usually the knowledge engineer collects knowledge based on already identified knowledge sources and carriers (e.g. experts, documents). It has to be considered that knowledge can be implicit, unconscious, incomplete, outdated or not applicable for a given case. Furthermore, communication problems between the expert and the knowledge engineer can appear. For the collection of knowledge, as a part of the previously presented knowledge acquisition, the following methods can be used: Interview techniques, text analysis, observation techniques or review techniques. Following up the knowledge collection, the knowledge analysis and structuring is carried out by the knowledge engineer (Luft and Wartzack, 2012a; Luft and Wartzack, 2012b; Schreiber and Akkermans, 2002). This process contains measures for the interpretation of knowledge and serves for the formulation of structures as well as the establishment of principles for the conclusion mechanisms. Therefore, especially the methods MOKA (Methodology and software tools Oriented to Knowledge based engineering Application, cf. Stokes, 2001) and CommonKADS (Common Knowledge Acquisition and Documentation Structuring, cf. (Schreiber and Akkermans, 2002)) are helpful. Thus, for analysing and structuring of knowledge relevant for the construction, the classification of knowledge in the following five categories proves (Stokes, 2001): *Illustrations* (e.g. engineering drawings) to clarify a complex issue, *Constraints* for the representation of mathematical relations between different quantities, *Activities* to describe the configuration process of the KBE application, *rules* for describing the target and current state as well as *Entities* for a principal description of the product structures (assemblies, subassemblies, parts) or a function.

Finally, the task has to be realized in the form of a KBE application which is called the knowledge implementation. It is necessary to transfer the formalized knowledge to a knowledge carrier that can be computer processed (i.e. the location of the knowledge (Roth et al., 2010), e.g. a digital knowledge base). Besides, the application has to be developed. The knowledge implementation is closely related to the knowledge collection because CAD design templates, design tables or other rules already exist. Within material carriers (e.g. data bases or documents), the knowledge can be saved digitally and made available for a KBE application. These includes, amongst others, CAD geometries in the form of intelligent geometry features, parts lists (with help of a PDM system), specialized knowledge bases and software programs that serve for automatization of construction tasks in CAD.

4.2.3 Test and Validation

In the test and validation phase, the decision relating the KBE project´s release for realisation is made. This decision is based on the documentation of previous steps and on the presentation of a prototype to the management. As a product, constructed with the KBE application can fail and consequential damages are possible if errors are overlooked, testing is very important. However, the effort regarding the test influences the lead time as well as the costs of the KBE project and therefore shall be proportionate to the risk.

For a successful use of the tests, an appropriate test preparation is important within the requirements phase, why it is necessary to define test cases or scenarios for all tasks. Finally, there are the following different types of tests which are performed by various persons or roles: *module or unit tests* (e.g. testing the CAD models, the knowledge basis or data given explicitly / implicitly), *integration tests, acceptance tests, regression tests* and tests in the *pilot phase*.

4.2.4 Operation

Following the validation and release of the KBE application, it can be implemented in the IT landscape and business organisation. Therefore, it is important to explain the reasons for the implementation of the KBE application in the company and to reach an appropriate organizational anchoring of the KBE application through relevant roles and responsibilities. Thus, the acceptance of the users can be ensured. Furthermore, professional courses and a continuous support of the users through knowledge engineers and technical experts are required. After the implementation and during the operation of the KBE application, it has to be administered, maintained and updated. Within this process, the topicality of the data based on the system (e.g. standard parts) and the definition of rules and responsibilities have to be ensured. Finally, a systematic change management is indispensable as objects of a KBE application (e.g. structures, geometrics) are often changed because of error-handling or expansions.

4.2.5 Security and knowledge protection

As CAD geometrics or CAD models are important knowledge carriers for a company, security and knowledge protection are relevant to competition. Thus it is possible to understand the modelling history and therefore the decision process of the designer by means of the CAD model tree. Moreover, CAD systems provide the opportunity of saving geometric knowledge with the help of rules or constraints and of depositing relevant information about e.g. tolerances and 3D annotations by so called PMI (Product Manufacturing Information) systems directly in the CAD model. Taking effective measures of security and knowledge protection is therefore very important regarding the designed parametric-associative and knowledge based CAD models. In addition to the fundamental security of the IT infrastructure (e.g. by firewalls), the IT security concepts “Digital Rights Management” and “Data Filtering” are advisable [VDI5610:2009].

5 IMPLEMENTATION - TECHNICAL SOLUTIONS FOR KNOWLEDGE BASED DESIGN

By means of a better understanding, a practical example of a KBE-solution will be presented in this chapter. Therefore, the next section offers an overview of existing CAx solutions related to their degree of knowledge-based support in relation to configuration and designing.

5.1 Classification of knowledge-based designing

According to the VDI guideline 5610 Sheet 1, knowledge-based design may mean both to design or develop a product as well as to compose several components to a product. Therefore, CAx solutions for knowledge-based design should not only support designing new products (domain layout / designing) but also composing existing components (domain configuration) [VDI5610:2009].
Different existing CAx solutions can thus be classified according to the degree of knowledge-based support for configuration or designing (see Figure 3) and be selected in accordance with the task. For the implementation of KBE-projects, especially the CAD related systems (dark blue coloured) are suitable. Thus, they are shortly explained in the following.

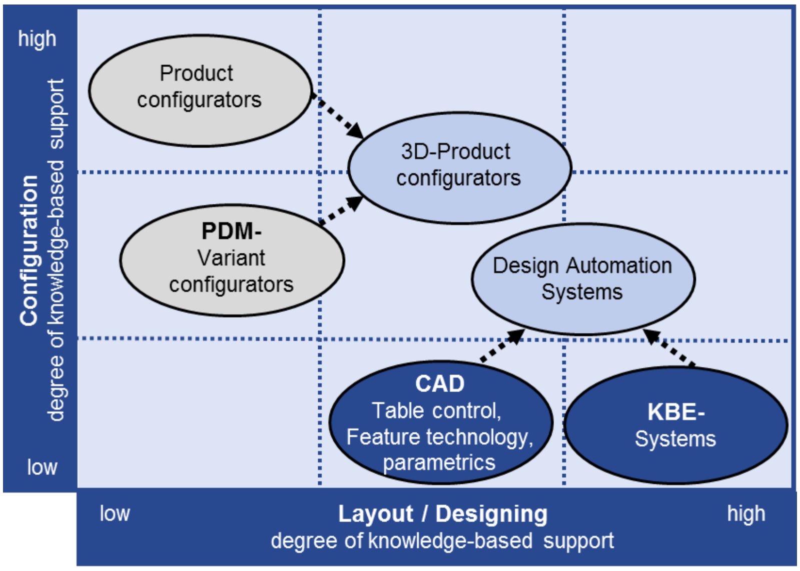

Figure 3. Classification of software systems (Lutz, 2011)

With **product configurators,** the rule-based configuration of individualized products is possible. They are used both in the consumer goods industry (e.g. configurators for computer, automobile) and the capital goods industry (e.g. configurators for pumps). **3D-Product configurators** serve for the position-compatible assembly of configurable components to a CAD assembly. Thereby, the object is to reduce the time for order creation and execution by means of the (web based) CAD support (especially through automatically generated CAD drawings). Due to knowledge based parametric (e.g. formulas), additional features (e.g. production information) and coupling to spreadsheet programs (e.g. excel), **CAD systems** provide many opportunities to the designer. **KBE systems** stem from traditional, knowledge-based systems which were gradually extended by engineer-specific functions (cf. also Beierle and Kern-Isberner, 2014). They basically contain efficient so-called problem solving components (also referred to as inference mechanism) as well as a knowledge base to manage rules and constraints. Furthermore, there normally is a close connection between KBE systems and CAD systems (or the CAD geometry). **Design Automation Systems** are extended modules directly integrated in CAD. They are used for the knowledge-based and automatic creation of CAD models. These modules use all construction functions that are available in CAD systems, whereby simple design tasks can be automated.

5.2 Solution example

This chapter exemplarily shows the implementation of a solution based on a KBE system (Figure 4). Therefore, the **initial situation**, the **target**, the way of project **implementation,** the **data and knowledge storage** and the **tools used** are specified.
The example is **based on** the parametrization of a CAD model (for example a throttle valve for petrol engine) and shows the potential integration of (amongst others) constraints and rules into the CAD model as well as the development of KBE applications in the form of component templates.
The **aim** of the example is the autodidactic communication of fundamental steps. Thus, the utilization of KBE basic functions in the CAD system can be learned.

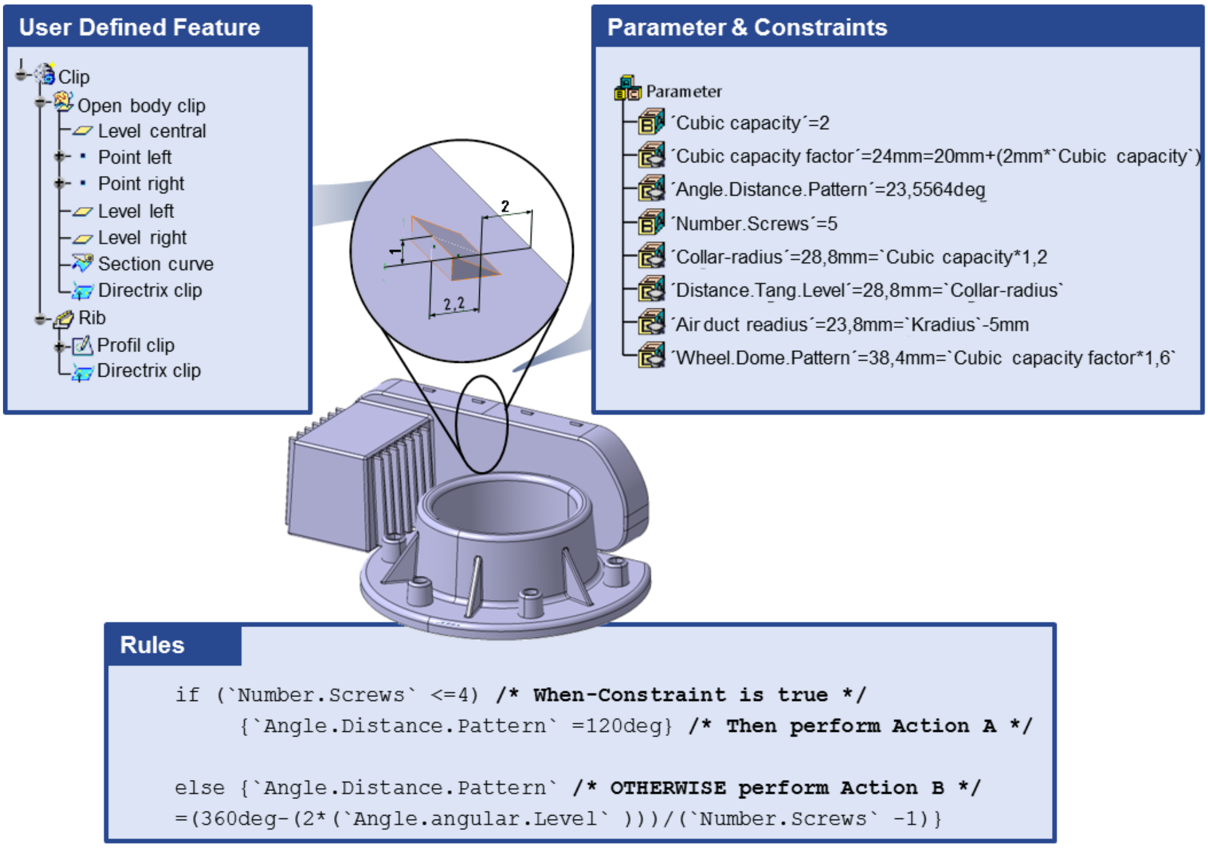

Figure 4. CAD model of a throttle valve with the saved knowledge

Within the **implementation** of the example, the parameters which steer the template´s behaviour are first defined. Regarding the throttle valve of a petrol engine, the cubic capacity of the engine is the determinative variable. The parameter cubic capacity is defined as a real value and converted into a geometric variable, the cubic capacity factor. Furthermore, additional geometric parameters as well as their interdependencies have to be defined and linked to the model parameters (e.g. distance, angle). Thus, the CAD model can be controlled via the parameters saved in the CAD model (see model tree,

Figure 4). The next step is the definition of logical dependencies by rules (Luft et al., 2013). Within the chosen example, the even distribution of the domes over the entire flange has to be ensured by an appropriate rule in the case of three fastening domes. A higher number of domes distributes evenly over the flange segment which is limited by the housing. It is also possible, to use a User Defined Feature (UFD) which can be understood as “partial model tree” und used at any points of a superordinate model tree. The linking of the feature to the subordinate part is just made via reference elements. Thereby, it contains all internal diagrams, bodies, relations, parameters or formulas. Finally, the design table is integrated. It can be created either within the CAD system or externally using table calculation software (e.g. MS-Excel) and enables to create standardised variants within a short time.
The **data and knowledge base** is usually integrated into the CAD model. Figure 4 summarizes the knowledge which is integrated in the CAD model. The **tools used** especially include the CAD system based on modern parametrical solid modelling. It enables the knowledge engineer to enter constraints and rules with the help of a graphical user interface. Thus, knowledge can be saved directly in the CAD tree.

6 CONCLUSION AND OUTLOOK

Summing up, this contribution presents as main component a procedure for the implementation of KBE projects. For this purpose, it has been necessary to clarify the principles of knowledge-based designing, as for example the underlying definition of knowledge, the process of knowledge acquisition comprising of three types (indirect, direct and automatic knowledge acquisition) as well as different typical forms of representation of knowledge (rules, constraints, frames).
Performing a KBE project itself, requires a systematic and general procedure. Such a procedure, developed within the VDI technical committee 111, consists of the four phases planning, development, test and operation which are briefly presented. As knowledge has been recognized as a central resource within the designing process, it is mandatory to protect this capital. This leads to the cross-sectional topic “Security and knowledge protection” within the general KBE process. This contribution also tries to give an answer how to organize roles within KBE projects and offers therefore adapted types (customer, expert, knowledge engineer, user) and brief explanations about their activities.
An initial impression of a KBE application demonstrates the interaction of knowledge and a CAD-system. This constitutes one of many possibilities in performing knowledge based designing. In addition, a general overview is given by the classification of software systems (Product configurators, KBE-systems etc.), comparing systems by their degree of knowledge-based support regarding designing/constructing and the degree of knowledge-based support regarding configuration.
Last but not least it should be stated, that the acceptance and application of such KBE-solutions depends strongly on their easy usage. As a consequence, the special concern of the superordinate VDI-guideline VDI5610 Sheet 2 is, to ensure that the user can draw on concrete and application-oriented recommendations and examples. Sheet 2 presents an extension of VDI-guideline VDI5610 Sheet 1 – Knowledge Management for engineering – and provides comprehensive support for KBE projects.

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