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# Concept Development of Design Driven Parts Regarding Multidisciplinary Design Optimization

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**ABSTRACT**

The increasing number of derivates in the automotive sector, combined with the product variation for individualization and technical progress, is presenting a major challenge for product designers. There are many case studies, especially in the concept development, which need to be checked on feasibility. This paper outlines how the necessary efficiency improvement, to deal with the rising amount of projects, can be achieved through the application of a Knowledge Based Engineering System (KBES). A special focus is put on the automated construction of design driven components. Furthermore, possibilities for the integration of expert knowledge into the construction system are demonstrated in order to enable a single user to build a product model according to the methodology of Multidisciplinary Design and Optimization (MDO).

An approach for the knowledge based creation of automotive headlamps is presented in detail. The advantages of a reacting construction system consisting of a variety of construction packages with feature integration is shown, as well as resulting possibilities of automated hedges, which do not demand any domain specific knowledge of the user.

**Keywords:** Knowledge Based Engineering, Multidisciplinary Design Optimization, concept development, expert knowledge.

## 1. INTRODUCTION

The product engineering in the automotive sector has to deal with several challenges nowadays. Although every year an increasing amount of cars need to be developed, the development time per vehicle must be shortened in order to reach the goals concerning the time to market in order to stay competitive. Additionally, the single subsystems are progressively getting more complex. In the automotive head lamp design, for example, there have been technological lunges within the past twenty years. In 1991, the first Xenon-lamp was used instead of a classic halogen illuminant. Today, LED is considered to be state of the art (first use in a headlamp: 2004) and the first laser-light within an automotive head lamp is already in series development. Additional features, such as adaptive-head-light or a glare-free-high-beam, have been developed to increase the safety of the driver. Additionally, head lamps are not only a functional component, but a symbol for the specific brand as well. Therefore, there is major attention in the media on the improvements of this product, which forces companies to apply several inexperienced technologies at one time. The application of new technologies and the realization of new design concepts result in many development loops. In addition, there is a customer-wish for individualization, which leads to a necessary variant management (within the shortened time period). This has an effect on the way engineers in the concept phase have to develop the three-dimensional product models which represent the basis for feasibility studies. To be able to perform the needed changes on these models multiple times, a completely parametric-associative model structure is necessary, which needs more time, due to the fact that additional construction elements have to be created. Therefore, the construction process needs to be more efficient. Another consequence is that the expert knowledge of increasingly different domains is necessary. The use of more powerful illuminants for example, results in a need for thermal calculations. For adaptive headlamp functions a kinematic hedge is needed, etc.

In accordance to the concurrent engineering strategy, all agents in the product cycle need to be integrated with respect to appropriate information exchange. For the purpose of creating an integrated design environment, computer tools are used to complement and assist the multidisciplinary team, giving the ability of each member to access a common product model data structure [4]. Therefore, 3D models are not meant to be just a virtual embodiment of geometry, but a data-pool as well [10], providing information for different experts. As there is typically an expert for every field, new problems arise. The first problem is that a specialist analyzes the product "only" in regard to his domain. As the subsystems in general have conflicting optimal solutions, a holistic perspective is necessary to reach a balanced global optimal design [1]. Hence, it is necessary to gather all experts for each product variation. "Indeed, before committing to any radical innovation, there is a need to generate an adequate knowledge of new concepts by means of detailed multidisciplinary analysis and simulations." [12] Even in series development, this is a huge challenge. In the concept phase it is not possible to investigate each domain and the behavior of the whole system dependent on that. There are too many different feasibility studies designed. Another problem is that experts working in a multi-project environment have to prioritize projects. As problems in the serial development have to be dealt with immediately, the concept phase is often not treated sufficiently, although it includes the highest potential for cost savings and reduction of the total development-time. The requested state is having a detailed product model already in the early development and that the constructor has the possibility to perform surveys concerning the different expert fields, which are important for the component. The usage of templates to reuse knowledge and existing design solutions is a common Knowledge Based Engineering (KBE) approach to accelerate the product development, which is nowadays well established [11]. Reviews on KBE can be found in [11], [17]. *Christ et al.* provide an overview of KBE and Feature Templates [5]. They also give the statements that this approach is most promising in adaptive design, where mainly geometrical details or shape-defining parameters are varied. There is still a need to develop systems that support designers with expert knowledge from different domains of the product life cycle.

This paper demonstrates how the necessary efficiency improvement may be obtained through the application of Knowledge Based Engineering with the focus on design driven parts. The intention is to show how a KBES enables one single designer to develop a product according to the basic thought of MDO, which by definition requires many iterations of (re)design and analysis processes that makes the improving of the level of automation, a fundamental goal [12]. A special focus is put on the practical use and the implementation into the routine business of BMW's head lamp development. In addition to that it is demonstrated, how the introduced system is having a didactic affect through implicit learning. Therefore, the theory of KBE will be explained in section 2. In the following section, an approach will be outlined how the problems mentioned above may be solved through a combination of automated construction packages and feature-integration. Section 4 will provide practical examples of integrated hedge functions enabled by the introduced construction methodology and further stored knowledge.

## 2. KNOWLEDGE BASED ENGINEERING SYSTEMS

Artificial Intelligence (AI), as a sub-domain of informatics, deals with the replication of certain abstract and computable aspects of human recognition and thinking processes on computer architectures, with the aim to provide problem solutions which afford intelligent performance by means of computers. A practical application is represented by the Knowledge Based Systems (KBS) [16].

The fundamental concepts of knowledge-based systems include:

- The separation of the knowledge from how it is used
- The use of highly specific domain knowledge
- The heuristic rather than algorithmic nature of the knowledge employed

Typically, the user interacts with the Knowledge Base System with a graphical user interface (GUI). From the user's point of view a KBS may be seen as an intelligent program which is linked to a problem-specific database. For the knowledge engineer, a KBS is divided into intelligent program and development shell as illustrated in Fig. 1 [9].

- Knowledge acquisition tool: Assists the knowledge engineer in the construction of the knowledge base
- Test case database: Consists of sample problems to verify improvements of the knowledge base
- Developer's interface: Same interface as seen by the end user, except that it contains additional features to assist the knowledge engineer in the development process
- Knowledge Base: Contains all of the relevant, domain-specific, problem-solving knowledge that has been gathered by the knowledge engineer
- Inference engine: Interprets the knowledge stored in the knowledge base respectively to the current problem

The evolution of Knowledge Based Systems towards the specific needs of the engineering design domain are called Knowledge Based Engineering Systems [11]. "The ultimate goal of the KBE system is

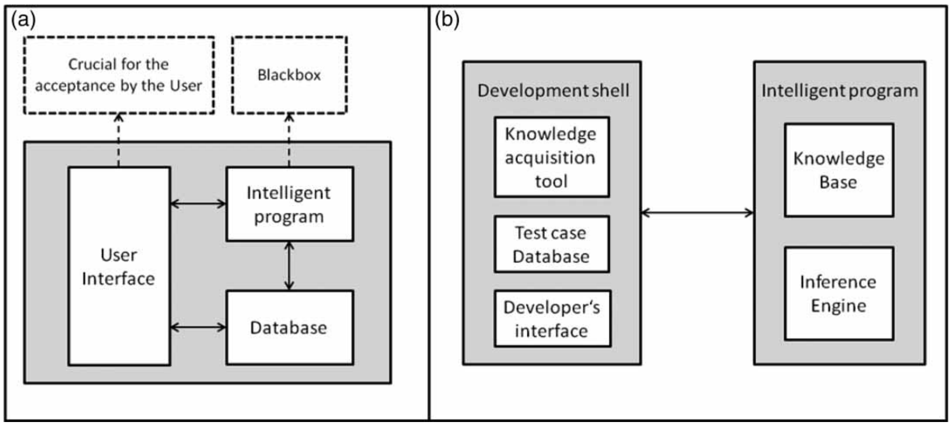


Fig. 1: (a) Users-, (b) Developers- point of view.

to capture the best design practices and engineering expertise into a corporate knowledge base" [4]. Therefore, the KBS is linked to Computer Aided Engineering (CAE) - tools and Product Data Management (PDM) - systems (Fig. 2). To accumulate and process gathered knowledge, a programming language is used. The choice depends on the software-systems which should be connected, the developing environment and the possibilities of creating graphical user interfaces. In terms of the software-components that should be linked to the system, it is important to look at the provided Application Programming Interfaces (API). It depends on the software producer, which objects and methods may be executed through the interface. Furthermore, state-of-the-Art CA-systems provide workbenches for an easy modeling of design knowledge. Examples are *Knowledge Fusion* of NX [15] or *Knowledgeware* integrated in CATIA V5 [3], which is used in the present paper.

## 3. AUTOMATION OF DESIGN PROCESSES

By the use of the KBE methodology, the user is freed from performing routine tasks, making more time available for the 'pure' design tasks and decisions [7]. The automation of non-creative design work automatically leads to an efficiency improvement of the construction process. Corresponding to this goal, KBE-systems concerning automated product modeling like CUMDA [8], the integrated system for moldbase design [13] or the approach of High Level CAD templates [1] have been developed. They follow the principle of instanciating User Defined Features containing semantic information. The KBES automatically adopts the implemented features according to the current project (to enable a fast and fully automatic product modeling.) "However, a modular model creation only makes sense if product variants resemble in their geometric characteristics" [8]. Hence, this approach is not sufficient for a design-driven part creation process. In this case it is not possible to provide basic templates which can be adopted to the current requirements by the combination with each other and the edition of parameters. There has to be a basic structure that can be applied to all possible inputs and be modified according to the changing demands. As the process of creating such of a construction and putting it into a macro-based system is very time consuming it needs to be determined in which depth it is economically sensible. Therefore, the structure needs to be arranged in a way that allows many routine tasks to be executed in loops. The main-routine must be kept short, consisting of heuristic knowledge, refering to sub-routines containing algorithmic knowledge that can be run multiple times. The maintenance and extensibility must be taken into consideration as well. Therefore, the KBES introduced in this paper can be used for all head lamp types of the BMW Group (BMW, Mini, Rolls Royce). The adaption of the system to rearlights is also considered, but will not be explained in this paper as it would exceed the content extent.

A central point of any KBS is the knowledge acquisition. This step needs to be divided into developer- and user- knowledge acquisition (DKA/UKA). The DKA is elementary to create the KBS. Information is gathered by interviewing experts, lessons learned, studying legal restirctions, etc. With the knowledge acquisition tool of the development shell this information is stored in the knowledge base and the inference engine is instructed how to use it. On the other hand, the UKA is the accumulation of information during the excecution of the system. The knowledge distribution between these two types affects not only the automation possibilities, but also the level of flexibility. The more predefined settings are made by the developer, the higher the automation grade. A disadvantage of the predefinition is decreasing flexibility, which is extremly important especially for design driven products in early stages. To solve this conflict, an automated construction method is introduced based on the idea of automated knowledge gathering during the construction process. By doing so, the highest flexibilty within the product range is given

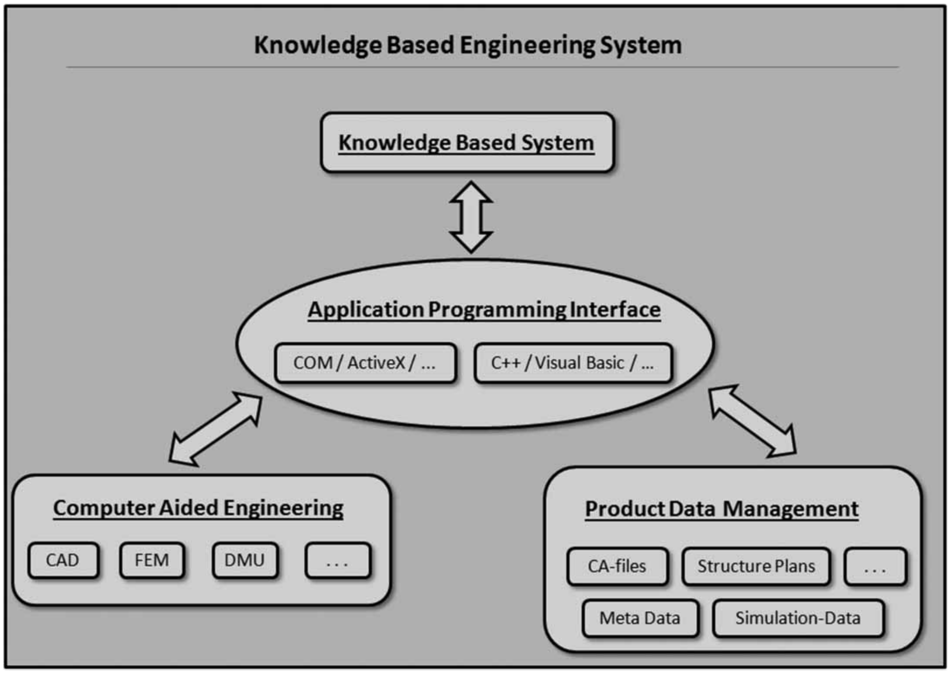


Fig. 2: Knowledge Based Engineering System.

without the need of UKA. The User must only select an input element in the 3D-CAD-System at the very beginning. Via GUI, the user has the opportunity to start the construction process. This is exactly what the KBES introduced in this paper is doing: starting the construction work! This means that there are no basic models which are modified by the system, but that the intelligent program recognizes the input and starts creating each individual hybrid shape, geometrical set or solid geometry on its own. For the example of a head lamp, the design surface of the outer face must be selected. Subsequently, the user has the opportunity to start construction packages over the graphical interface. These packages may contain thousands of single construction steps depending on how reasonable the size of the bundle is. As the KBES is doing the non-creative work for the user, he or she may be given the opportunity to do his or her actual job, the creative aspect of the design during the operating system. Therefore, the generated elements appear and may be manipulated in the CAD-structure in the usual way. After potential adaption of the model, which is not always necessary, another construction package can be run. By starting a macro, the system is retrieving information of the current model and manipulations by the user are recognized. If adjustments are necessary, there is not only the opportunity to perform changes parametrically, but also rearrangements of the entire structure as each single element is known to the system which created them (Fig. 3).

As the system always displays the next useful step, the designer is guided through the creation process of the 3D-model. This means that the time needed, enabling the user to work on a high level, converges to a minimum and the use of the KBES has a didactic influence. By using the system the user is learning the sequence of the procedure in an implicit way, which is per definition, acquiring new information without intending to do so, in a way that the resulting knowledge is difficult to express [6]. Working in the 3D-CAD environment, individuals are able to reconstruct each step that is included in a package. For an easy control of the 3D-model by intuition, only the control-elements are displayed (Fig. 4), but all other objects are stored in the date file as well. There are also information-buttons providing instructions for each step. Whenever the system is restarted, it is also gathering information of the part model to offer the appropriate step according to the current state of construction. This allows for an easy exchange of CA-models during the construction process between different designers. Furthermore, a layer for optional macros is implemented in the user interface, allowing additional functions for the user, which are not mandatory to create the model, but instead help in the control of elements.

Furthermore, this methodology allows the implementation of new specific functions like the so called *concept offset*:

To obtain a clean, flexible and easily controllable outer surface of the head lamp lense, a parametric grid structure consisting of control sketches, with limited degress of freedom to avoid intersections, and B-Splines is set up and filled with Multi-Section-Surfaces (MSSs). The splines are organized in rings which build

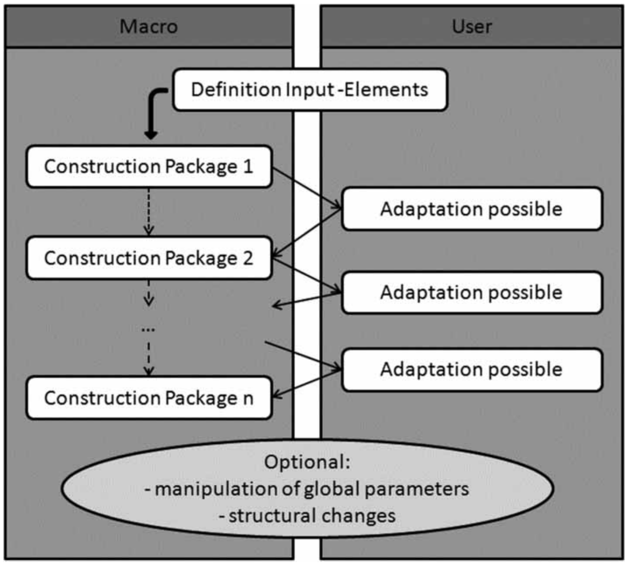


Fig. 3: Design automation via construction packages.

the model from the design face in the direction to the back of the car. The tangent direction of the Splines of the first "ring" (of the grid structure) are oriented to the boundary of the input face. The other Spline's tangent directions use the Spline one ring above as input. On every point of a sketch where two Splines meet, they have the same tangent direction to get a smooth curve. As these curves serve as input for the MSSs, they have a tangent continuity within one ring as well. From one ring to another the consistency is ensured as they always share one Spline-ring, but there is no tangency garanteed because sharp edges have to be realized often. Through this composition, it is possible to create the complex form which is needed to fullfill all requirements, but it is extremely difficult to offset this surface to generate the volume body. This ends in a trial and error process. As long as the offset can not be calculated, the user needs to modify the surface according to the displayed errors. However, the KBES creates a second grid structure depending on the parent grid. Therefore, each spline, surface and part of the sketches is re-created and offseted in the defined wall thickness, which can be controlled through the GUI. The goal is not to create a perfectly smooth surface, but to obtain a consistent face, allowing the creation of a volume body, so that package describing models can be researched as fast as possible in the early stage. As the distance may vary somewhat from the defined value, this method is called concept offset, because in the early phase this small variation is not as important as a quick robust process. Nevertheless, there is an optimization routine included that minimizes the variation by scaling the spline tensions. Since each individual element is already known to the system with which they were constructed, this results in a one-click solution.

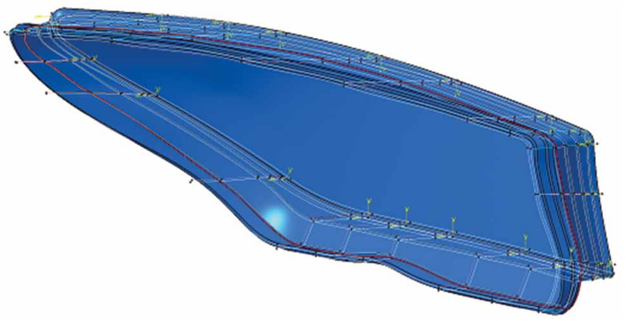

Fig. 4: Volume body with control elements of a head lamp lense.

In order to obtain a model of the entire head lamp, there is a basic product structure available in the Product Data Management (PDM)-system. Within this structure there is no geometry, but links to the design parts like the lense or housing for example, in an organized way, instead. This allows an easy maintenance of each part on its own. By loading the product, the PDM recognizes the newest version of each linked instance. The structure also contains unreferenced units which have semantic knowledge included. For a parametric-associative setup of the entire component, the geometry exchange between single parts is managed by the KBE-system. Therefore, further needed elements are recognized, published and copied with link to the corresponding part, which may start a construction package itself, as soon as the necessary inputs for the package are available (Fig. 5).

The approach for implementing adoptable user defined design features, as mentioned above, will be applicable in this work as well. Such features containing geometry, as well as semantic knowledge, can be selected and positioned with the graphical interface. Positioning-modules are created, which define an undisputed localization via three points, to which the prepared geometries may be referenced to. Standard elements like illuminants can be inserted with all information necessary in the further development process. Furthermore, parameterized reflectors are linked to the bulbs or LEDs (Light Emitting Diode) and adjusted. As the inference engine and the knowledge-base are separated in this expert system, it is easy to add or modify knowledge pieces inside the knowledge-base [14]. An EXCEL-file provides the information about which features are available and how they are linked to each other. This way it is easy to enlarge the catalog without any knowledge about programming. Elements like lids, control devices or connectors may be integrated with the corresponding attachment to the housing. The positioning is controlled in a central composition part, which enables an easy positioning of the element itself and the attachment which is included in the housing part, for a fast and easy trimming (Fig. 6).

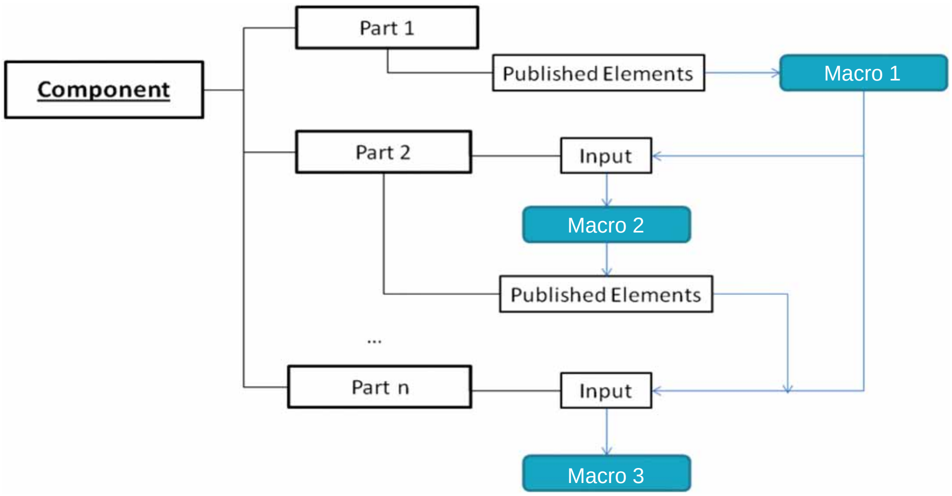


Fig. 5: Automated linking and starting of construction packages.

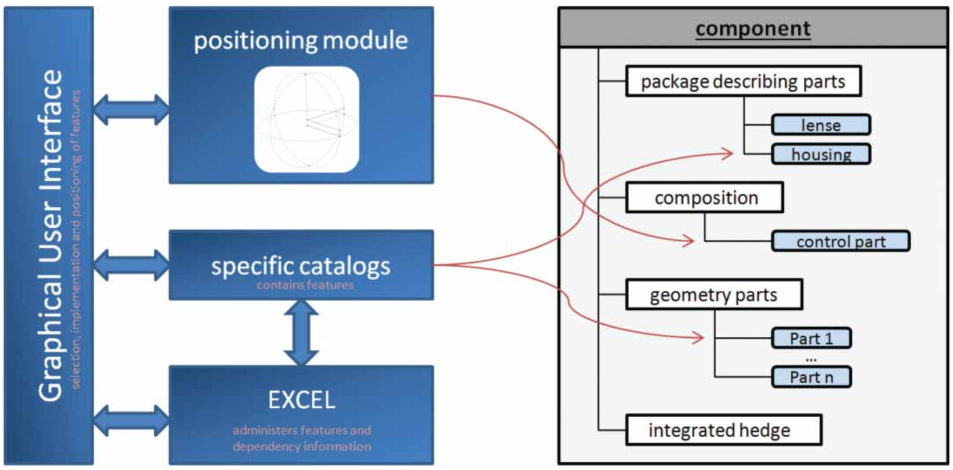


Fig. 6: Feature instantiation

## 4. INTEGRATED HEDGE

Each concept needs to be checked on feasibility. The earlier this occurs, the less temporary and monetary expense is caused by changes. As a consequence, the restrictions of all domains involved and their influence on one another should be reviewed as soon as possible. To implement this approach in praxis the KBE-system introduced in this paper contains all the information needed for different hedges, as well as methods to support the user running tests for single parts, as well as the component as a whole. Complex simulations may be included as well as one-click-solutions which are demonstrated by three examples:

1. For injection molding parts, the demold-ability is an important manufacturing-criterion. The amount of sliders and their direction of demolding are of great significance. As the separation lines between sliders are visible, the positioning is very important for parts with high demands on design. In order to check this issue, the user has the opportunity to define an optical attractive separation course and start a macro to control the feasibility. All of the required geometrical information exists in the knowledge base. The combination of different demolding directions, for which a manufacturing is possible, is listed in an EXCEL-sheet.<?pag ?>
2. The communication with other development departments, in the early development phase, is based on sketches containing specified elements. Their position is dependent on the position of the illuminants. The system knowledge of each constructed or integrated geometry enables a data exchange with one click. Therefore, all necessary parts are recognized and intersected with the support planes for the exchange sketches, which are created on demand by the KBES. The specific elements

contain string parameters called "light axis". Their values describe the amount of axis included. Whenever a feature is implemented, the KBES recognizes this parameter and adds information to the property parameters of the part in which the feature is integrated. Whenever the sketches for the integrated car body development are needed, the system is searching through the basic-structure by reading the property parameters of each part document. The coordinates for the positioning of the light axis and the corresponding planes are extracted. Based on this information each volume body can be intersected and the consequent wireframes are joined. The result is appended to the basic structure.

3. Intelligent parts within the basic structure supervise the compliance with legal restrictions concerning luminous faces. The particular elements are recognized and monitored with the CAVA (CATIA V5 Automotive Extensions Vehicle Architecture) application, a collaborative project of Transcat, BMW, Audi, Daimler, Porsche and Volkswagen [2]. *Reactions*, created with the CA-integrated *Knowledgeware*, are stored in the part documents in order to recognize the relevant faces and communicate them to the CAVA application. This may happen in three ways. By implementing a feature, the knowledge, about the luminous faces and which function they fulfill, is contained in the feature itself. If an object gained by automated construction packages similar to the lense, the necessary information is stored in the knowledge-base. If the user is designing in the common way, there are Output-Sets within the basic structure, where the luminous faces have to be saved in, which are supervised by the *Reactions*. As a result, all surfaces and the functions they are assigned to are known by the CAVA application without any effort. Whenever a change to a legally relevant object is performed, the user receives information as to whether or not a rule is broken and if so, which one. A specific requirements-profile has been added to ensure that a worldwide homologation is possible. Furthermore, the information about the homologation documents is stored in the KBES. Whenever necessary, an EXCEL-document can be created containing all nominal- and actual-values necessary for the homologation plus pictures and additional information of the component derived from the 3D model.

For functions like the headlamp beam height control or adaptive-head-light, a defined free space within the component has to be determined to ensure a proper movement. For package investigations it is necessary to compute the volume which describes the exact area. The basis for this computation is a multi body simulation of the actual behavior of the kinematic system. Setting up such a simulation requires expert knowledge of headlamp-mechanics, as well as experience in creating computer aided

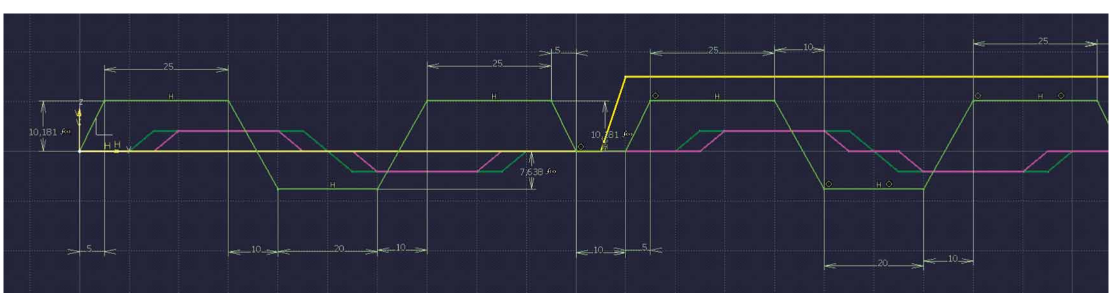

Fig. 7: Command Control Sketches (X-Axis: relative time step; Y-Axis: f(movement range, coordinates, command definition)).

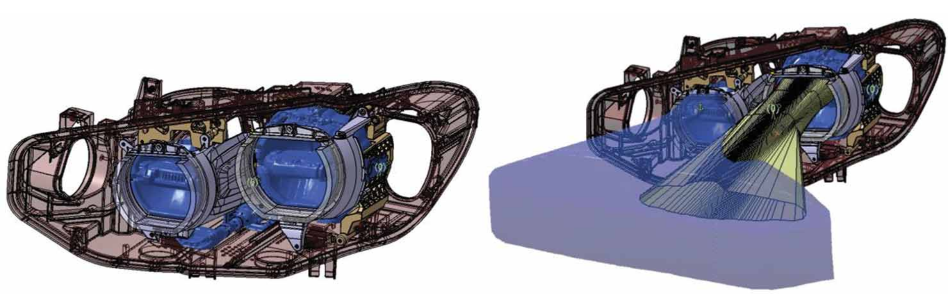

Fig. 8: Swept volume of kinematic parts (and light cones) of a BMW 4 Series Coupé LED head lamp.

three-dimensional kinematic simulations and moreover, a great deal of time. With the goal of giving any user the opportunity to perform such an analysis and accelerate the process, the basic mechanisms of different suppliers are stored in the knowledge base. They are broken down into adoptable coordinate points. The points of articulation of the current model have to be selected by the user or comply with name conventions to be automatically recognized. For the movement range default values are set, which can be customized in the GUI. These values are included in trigonometric equations that also contain joint coordinates and command definitions like thread pitches. The sequentially or simultaneous actuation of the commands is controlled by sketches which refer to those equations (Fig. 7). Light cones may also be included in this analysis to gain information about possible unwanted reflections or dimming of the beam (Fig. 8).

Another important issue that needs to be checked in the early stage is the thermal expansion. There are typically four points of attachment between a head lamp and the car body as shown in Fig. 9. Dependent on how these points are positioned, the thermal expansion may lead to a rotation of the component,

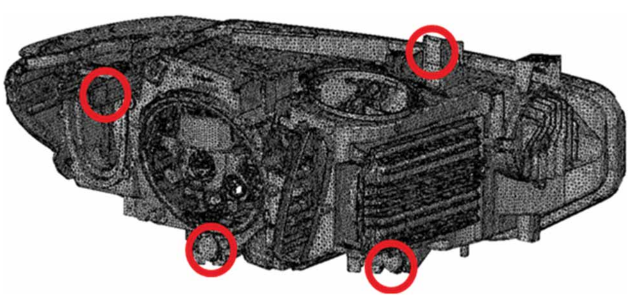

Fig. 9: Attachment points.

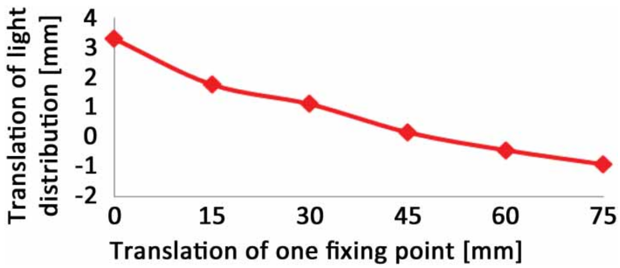


Fig. 10: Manipulation of one attachment point.

having a major impact on the light distribution, which is measured on a wall 10 meters in front of the lamp. This influence is usually simulated by the supplier in the serial development if there are problems fulfilling the restrictions. Due to the fact that the positioning of these points is also important for other components, they are fixed quite early in the development process. A more sensible way would be the simulation in an early stage, providing the chance to modify the problematic elements. Therefore, investigations on Finite Element- (FE) calculations with different attachment-points have been made. The deviation of the light distribution was computed on the 10 m-wall (Fig. 10).

To enable such an examination for each study and all constructers, a fast and full automatic process is necessary. The discretization of the part is an important step. Therefore, the KBE-system provides simulation-ready data quality as input for the FE-process. The system extracts a state without problematic elements like roundings, small drillings, etc., as it knows the construction history by scanning the part-structure, no matter how detailed the construction already is. It runs a test whether the meshing is possible or not. If the test is negative, the process is repeated with an earlier design version. The system-controlled positioning of the attachment-elements

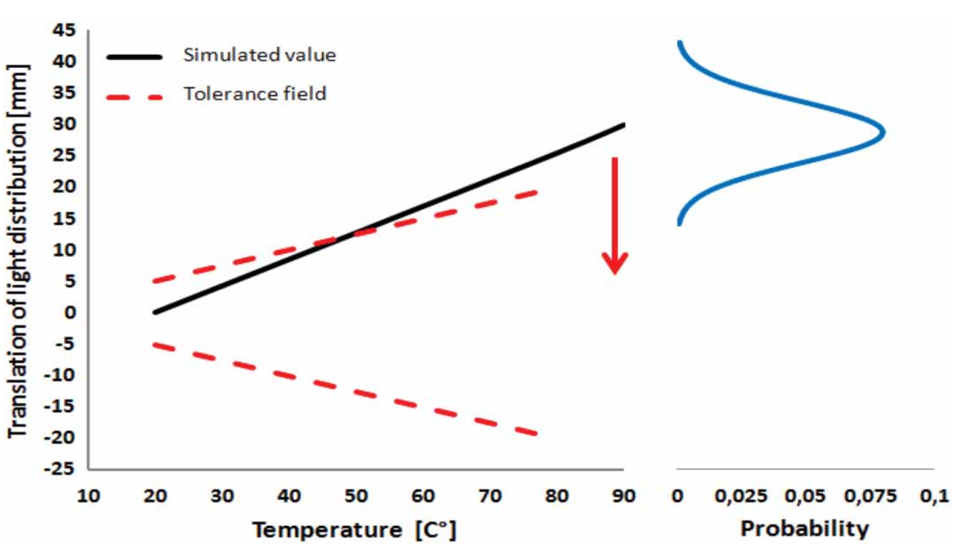


Fig. 11: Possible incident prediction.

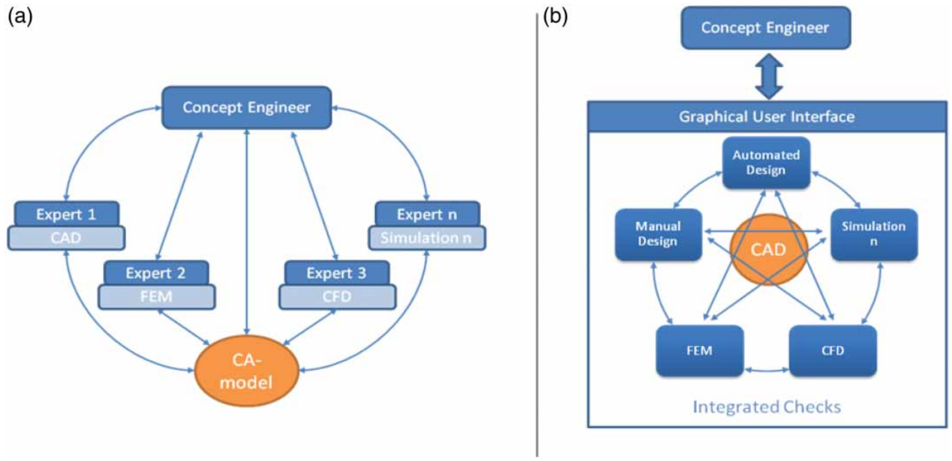


Fig. 12: (a) common process, (b) Knowledge Based Engineering System.

makes it easy to run optimization loops in order to find a combination that equalizes the thermal effect concerning the rotation of the headlamp. It should also be mentioned that the behavior can only be predicted in a certain accuracy because of the missing level of detail, but serious problems can already be prognosticated and eradicated (Fig. 11).

## 5. SUMMARY AND CONCLUSIONS

The introduced approach demonstrates how, through the application of KBE, a toolkit containing expert knowledge of different domains may be provided to a user enabling him or her to create a product model according to the basic thought of MDO in an efficient way (Fig. 12). As the system allows the user to run CAD-based automated simulations, there is a decreasing need of experts to hedge feasibility studies in the early development stage. The system is not only saving up to 80% of construction time (depending on components complexity), it also reduces the time for automated simulations and following processes, which need meta-data that is already stored in the knowledge base in an appropriate way for the respective specialist. Further research is necessary for the integration of lighting simulations. It has to be clarified how state-of-the-art Computer Aided Lighting (CAL) – software can be integrated in a KBES to give the user the possibility to evaluate his or her construction of the entire lighting system. Furthermore, it is outlined that the developed system has a didactic effect on the user. In the future proband-studies on equal test cases have to be performed to estimate the didactic effect and to find out how this effect can be improved. The explained method describes how the demold-ability can be checked with one click. Additionally, it represents the base for a tool which, in case of a non demoldable part, modifies this part until it can be produced this way. This is possible as the conflicting areas can be found and the system can retrieve and adopt the elements of the basic structure of the model.

A very high and consistent data quality, which is necessary for further development steps can be obtained after a very short learning term. The quality, in general, is consistently on a high level regardless of who created the model.

The proposed methodology is already in practical use in the concept development of the BMW exterior lighting department. It is continuously being further developed by BMW in collaboration with the Institute of Product Engineering at the University of Duisburg-Essen.

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