An Expert System for Design-Process Automation in a CAD Environment

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Abstract— **For enterprises operating in markets, where customer needs can only be fulfilled with highly individualized products (which in turn necessitate a high degree of variety of lines of products), finding ways to reduce design and manufacturing costs is a crucial issue. This paper presents an expert-system approach to help solving correspondent challenges. The main methodology applied is to separate the design process into creative and repetitive tasks: Mapping the design logic of repetitive tasks onto a knowledge base then facilitates the creation of an expert system. This system supports engineers by automating those portions of a design process, which are based on repetitive tasks. Thereby, design-task complexity is reduced und there is a significant speedup of up to 90 % within construction processes. Finally, such a system enables engineers to focus on creative, value-creating tasks.**

Keywords— Expert System; Knowledge-Based Engineering; CAD

I. INTRODUCTION

Companies try to fulfill customer needs. For a manufacturing company, this can result in an extensive number of assemblies and parts, in order to cover the specific needs of every customer. Since this approach is very costly regarding development and production, enterprises aim at optimizing their costs while still maintaining the possibility of satisfying their customers.

Liebherr-Werk Nenzing GmbH (LWN) [6] is a manufacturer of a wide range of products including ship-, offshore- and harbor mobile cranes as well as hydraulic duty cycle crawler cranes and lift cranes. Its mission is to fulfill customers' needs. While standardization is possible in many of its products, there are also segments which require adaption of the crane to specific market demands. This results in a partial or complete engineering of a crane. In particular, the design of ascent assemblies and boom boxes for offshore and ship cranes (see the following section "Business cases") results in substantial efforts and constitutes a major part of the overall engineering costs.

As a result of this situation, LWN intended to minimize these costs by improving the design process in close co-operation with the industrial research centre V-Research in order to analyze possibilities of optimizing the development process and of reducing design and production costs.

By investigating the design process of ascent assemblies and boom boxes, we found that the design process is mainly based on repetitive tasks. Consequently, designing those assemblies is based on a set of invariant rules that can be modeled and stored. The only exception is the structural analysis of the assemblies. The results showed that the statics of ascent assemblies can be represented by rules. However, the statics calculations of boom boxes are more complex. To verify static stability of these assemblies, dedicated structural analysis simulation algorithms have to be integrated into the design process.

Furthermore, the current building blocks of the assemblies were analyzed. By doing so, we pointed out that a high amount of part variants existed, which in turn led to high costs. To reduce the number of part variants, we proposed to develop a fixed set of standardized parts, which is sufficient to designing all required assemblies.

These prerequisites enabled the standardization and optimization of the engineering process of nearly all ascent assemblies and boom boxes by automating the design process. The result of this approach is an expert system that permits more efficient design of the described assembly types.

This paper starts out with a short overview of related work. After presenting the business cases underlying our approach, this paper continues with a detailed explanation of the concept of the developed knowledge-based engineering (KBE) application. Then, the developed interfaces of the KBE-system and the resulting software framework are detailed. The paper closes with a short case study, summary and conclusion.

II. RELATED WORK

The result of our research was that there are product configurator approaches, which solve configuration problems automatically.

In the field of Artificial Intelligence, a configuration problem is understood as "the generation of a structure with predetermined properties by means of the combination of a certain number of objects" [4]. Bourke expands this definition and describes a product configurator as "[...] software modules with logic capabilities to create, maintain, and use electronic product models that allow complete definition of all possible product options and variation combinations, with a minimum of data entries and maintenance" [2].

Sabin et al. classify product configurators according to their concept of configuration knowledge as rule-based,

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model-based, and case-based product configurators. According to them, each approach represents the configuration knowledge and the instances of the product to be configured in a different way [9].

In [3] Brinkop presents a list of leading providers of product configurators.

The expert-system approach presented in this paper starts one step before product configuration: based on user-defined assembly functionalities and a design knowledge-base (i.e. not only a configuration one), all parts are first generated and then assembled. Furthermore, the whole design process of a specific product is supported: Apart from a 3D CAD model, production drawings, bills of material and the production costs are provided as well. That is, the whole engineering process is automated.

III. BUSINESS CASES

LWN defined two assembly types, which served as business cases for our research: ascent assemblies and boom boxes. Design efforts and production costs related to these parts were rather high.

On the left side of fig. 1, an offshore crane is illustrated. For maintenance and inspection, several strategic points on the crane have to be easily accessible. Therefore, an ascent concept has to be developed, consisting of multiple ascent assemblies (platforms, stairs, ladders or roundplatforms). In the figure, they are highlighted in red.

On the right side of the image, a ship crane is shown. For this crane, the boom has to be engineered to fulfill specific customer requirements, consisting of lifting capacity as well as of working and interference area. These requirements are derived from the ship design of the customer and allow for little variation. Therefore, the boom section highlighted in red is designed individually for each application. This type of boom consists of a pivot, a middle and a head section. The middle section, representing the second business case, consists of bottom, top and side plates as well as stiffeners and bulkheads. Their dimensions and their quantity depend on the results of the structural analysis. This complex analysis is performed based on the customers' requirements.

IV. CONCEPT OF A KBE-APPLICATION

The objective of our approach is an expert system. According to Steinbichler [10], an expert system is a system, which stores and accumulates specific knowledge of different areas and generates solutions in a user interface to given problems. Leondes [7] extends that definition by equating the terms "knowledge-based system" (KBS) and "expert system". He clarifies that a knowledge-based engineering (KBE) system is a subset of a KBS. According to Stokes [11], knowledge-based engineering can be defined as "the use of advanced software techniques to capture and re-use product and process knowledge in an integrated way." To use the KBE-approach, users' expertise has to be acquired and stored. The captured knowledge is then permanently available. Hence, the product development can be regarded as a holistic process. All relevant design know-how can be extracted and mapped onto the product model [4].

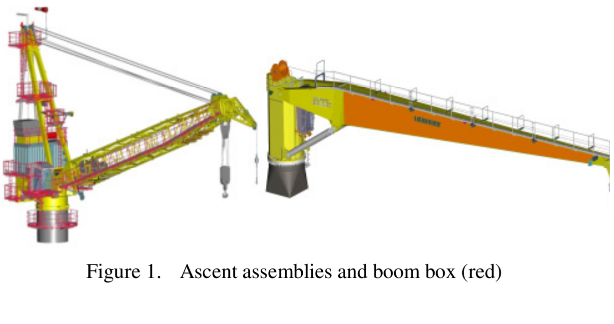

Figure 1. Ascent assemblies and boom box (red)

Concerning the approach of this paper, KBE is based on an IT application of high usability that supplies and processes knowledge and interacts with a CAD system. The result is an automatically generated solution, in accordance with a designer's input. The CAD system itself is completed with explicitly modeled knowledge in form of a programmable application. This knowledge contains all information about a product, i.e. its structure, function and behavior as well as its manufacturability and quality. This is all the data a designer has to know and to enter into a CAD system.

Based on the previously explained methodologies and requirements of LWN, we developed a concept for integrating KBE-design and structural analysis.

The concept relies on some restrictions and approaches which are explained in the following subsections.

A. *Influencing Factors*

To model a design process, it is necessary to investigate all influencing factors. Engineering of assemblies is based on a variety of restrictions, namely:

- industrial and internal standards
- statics requirements
- production costs
- implicit design restrictions (e.g., assembly erection or maintenance aspects) and
- production restrictions (e.g., disposal factors)

For example, if designing a platform, these restrictions are special assembly logics or platform entries conforming to standards.

B. *Modelling of the Design Knowledge*

To build a KBE system, the relevant engineering expertise has to be acquired. Our analysis showed that engineering processes can be differentiated into repetitive and creative processes. In contrast to creative processes, repetitive ones consist of nearly identical tasks and are therefore independent of creative decisions. This condition is necessary for modeling them as a system of rules.

In contrast to repetitive processes, creative ones occur typically only once. Because of that, modeling them as rules within reasonable time is economically not viable.

One of the goals defined by LWN was that a specific repetitive design task should always result in the same, ideal solution. Because of the limited ability of a human to reexecute cognitive tasks identically, it is important to support users with a tool (i.e. a software application).

To fulfill this goal, and to capture all relevant steps for designing the focused-on assemblies, we conducted numerous interviews with engineering experts at LWN. The retrieved information served as a base for analyzing the repetitive design processes. Most of the time spent was used for detecting the restrictions defined in section IV.A.

The obtained data were prepared to be stored as rules in an IT system. These rules represent directed dependencies in a form common for expert systems, namely "IF (condition/-s) THEN (action/-s)", i.e. all conditions must be known and must be fulfilled before a rule can be applied [4].

The rule set can be used for arbitrary types of assemblies. Rules can be changed without editing the source code. In addition, if a full range of rules is acquired, nearly every form of assembly is supported. Therefore, repetitive tasks in designing new or adapting existing assemblies can be automated. This enables engineers to focus on creative, value-creating activities [12].

C. *Decision support by cost optimization*

The elaborated automation algorithm follows the explained system of rules. To evaluate all design alternatives, the resulting combinatorial programming problem is based on standardized manufacturing costs. These costs were retrieved by an analytical method which analyzes bills of material and task schedules [13].

All engineering tasks, which are not covered by this system (e.g., structural analysis of booms) are integrated in the expert system by defining an interface for data exchange with external applications.

Based on the defined customer parameters, e.g. maximum lifting capacity as well as working and interference area, the external applications calculate a weight-optimized geometry of an assembly version. However, due to the nature of the boom production processes, a weight-optimized geometry is not necessarily cost-optimized. Based on the resulting structure, the developed algorithm uses a defined set of rules to translate the calculated geometry into a cost-optimized structure, while still adhering to the boundaries of the statical calculation. The final result is an assembly that is cost-optimized and statically verified.

This algorithm guarantees an optimal design process for the considered assemblies.

V. Interfaces of the KBE-Application

The above described approaches are fundamental to the developed expert system.

In the following sections, the most important components of the application are described.

A. *Man-machine interface*

The graphical user interface is an important component of the developed application. This interface is used to exchange data between a user and the algorithm. Our focus was put on minimizing user input. The goal was to allow users to define an assembly as efficiently as possible. Finally, design engineers only have to provide data which cannot be retrieved automatically. Furthermore, they are supported by interactive sketches. Inputs are immediately visualized (see fig. 2).

Every irregularity as to a defined process is highlighted by interaction dialogs. For example, if a design engineer defines inconsistent data, the application alerts the user.

In addition, a user is supported by some assisting tools. One of them is concerned with the combination of assemblies: there is a wizard that visually supports the user to form a valid combination of assemblies (e.g., a complete access solution for an entire crane) (see fig. 2).

B. *CAD-System Interface*

1) *Component Assembly*

Once an assembly is defined by the user, and, if necessary, the structural data are calculated, the respective data are then handed over to the automated design-to-cost algorithm. After calculating all necessary information for generating a 3D CAD model, the computed data is sent to a CAD software in an iterative way, using the application programming interface (API) of the CAD system.

First, each part is loaded and, if necessary, the geometry is adapted. Then, the parts are positioned in reference to an existing part to ensure that all parts refer to each other. This is important because as a result every manual change directly affects all parts. For example, if a user manually changes the length of a part, the positions of all dependent parts are adjusted automatically.

This principle has also been applied to assembly combinations.

2) *Production Drawings*

To complete the design process, production drawings have to be generated. As a consequence, the developed application also generates these documents automatically.

In order to efficiently use the space available on the drawing sheets, the positions of all required views are calculated by an algorithm based on trim optimization. To

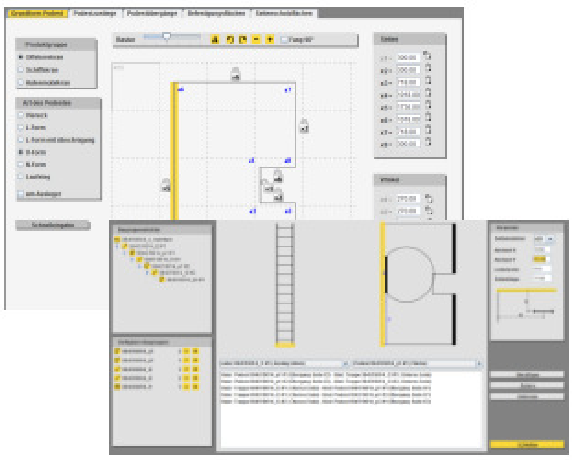

Figure 2. Example of an interactive sketch for assembly dimensions and an assistant wizard for assembly-combination definitions

ensure a good and fast solution, the concept of trim optimization was simplified. Each view is reduced to a rectangle or a combination of it, which is put at the most appropriate and still available position.

After all views have been positioned, all production-relevant dimensions and the according measurements are automatically added by a generic framework. This framework is implemented with the API, provided by the CAD system. It is based on a classification of dimension types. Dimensions can relate to

- an edge
- an edge to point
- a point to point or
- an angle.

For every mentioned type, a dedicated positioning function has been implemented.

Finally, the bill of materials is added to the drawing.

C. Structural-Analysis Software Integration

As each individual boom box requires a separate structural analysis, we developed a method that is based on a KBE-system which interacts with a structural analysis system (ANSYS).

1) Structural Complexity of Boom Boxes

From a statical perspective, ascent assemblies and boom boxes are designed to carry load. However, construction principles differ significantly between the two.

Ascent assemblies contain specific components, which ensure the adequacy of the design according to safety and overall requirements of the structure. Based on these parts, there is a limited set of variants with a fixed geometry. As a consequence of that, all statically relevant components can be pre-calculated by using suitable software. The resulting parameters, e.g., the maximum load per square millimeter or the maximum gap to the next structurally relevant component, can be pre-assigned and therefore stored in rules. For example, the base frame of stairs consists of stringers. However, the main static load is carried by cantilever arms. In order to guarantee the stability of each assembly version, depending on its dimension and based on the precalculated statical parameters, the number and/or dimensions of these parts may vary.

In contrast to the described ascent assemblies, all components of a boom box are structurally relevant elements. Because of the market-segment specific requirements and due to LWN’s commitment to fulfill them (i.e. to provide arbitrary lengths and loads, according to customer demands as to boom boxes), their dimensions largely vary and cannot be limited to a standard set of parts.

Furthermore, different load scenarios have to be considered when designing a boom box. Because of that, a structural pre-calculation of every possible dimension of the individual components is not possible as the boom has to be considered as a complete system. Therefore, the statical logic for boom boxes cannot be mapped to simple rules regarding its components. Nevertheless, an integration of the structural analysis into an automated process is possible and has been realized in the scope of this project.

2) Interaction with the Structural-Analysis Application

In [6], the author defines structural analysis as follows: “Structural analysis is a process to analyze a structural system in order to predict the responses of the real structure under the excitation of expected loading and external environment during the service life of the structure.”

A standard structural-analysis process is shown in fig. 3. This process works for boom boxes at LWN in a similar way. In a first step, the design manager of the project converts the customer requirements into load cases. A load case mainly consists of a boom position (inclination angle) and a load capacity. After taking into account additional factors, a set of load cases is generated.

Based on this input, a simplified model is generated and processed by the structural analysis software (ANSYS). In ANSYS, the model is analyzed with all the load cases. Based on multiple iterations, the defining parameters of the components (e.g., plate thickness) are optimized.

The result is an iteratively calculated optimal structure of a boom box. For each section, the material dimensions, part quantities and positions are defined. Based on these data, the CAD model of the boom can be generated.

As the existing structural analysis procedure is a very time-consuming, complex and effort-intense process, we tried to simplify and increase its efficiency. In the end, we automated nearly all manual activities and integrated them into the developed KBE-system.

To supply the structural analysis software with all relevant information, we developed a standardized data exchange format. Now, the only manual activity consists of defining the load cases based on customer requirements. The developed algorithm then transforms these data into an ANSYS-suitable configuration and hands them over to the structural-analysis simulation application. Once the simulation has started, no further user interaction is necessary. At the end of the simulation process, the structural

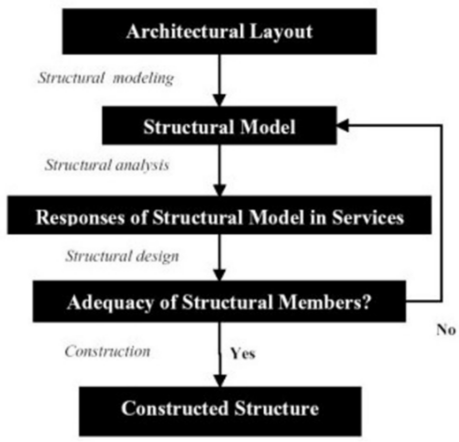

Figure 3. Structural analysis process

engineer receives all the data for double-checking.

For returning the results to the KBE-system, an additional interface format was developed.

Finally, the calculated assembly structure is statically optimized. The utilization of the material is maximized and as a result, the weight of the total structure is minimized. However, as stated before, a weight-optimized structure does not necessarily mean that it is cost-optimized. Therefore, based on a set of design rules, the KBE-system translates the data to achieve a cost-optimal solution and generates a CAD model as described in subsection B above.

By employing this approach, the development process of a structurally complex assembly becomes significantly faster and more effective. This also enables LWN to react quickly to changes in the requirements of a customer.

VI. OVERVIEW OF DEVELOPED FRAMEWORK

Fig. 4 visualizes all components of the here described software. For data exchange, the framework provides several interfaces. These are prepared for assembly-independent use. The brown boxes in the center of the below figure represent the developed algorithm. Since an in-depth explanation of all these modules is beyond the scope of this article, we dispense with details.

In order to prove the generic character of the developed framework, we used it for the design of the two above discussed business cases (ascent assemblies and boom boxes) as well as for houses on stilts (i.e. an illustrative case for an open-house day).

VII. THE EXPERT SYSTEM IN PRACTICE

As explained in the previous section, we used our framework for the engineering of ascent assemblies, like platforms. To illustrate design and functionality of the KBE-System, fig. 5 illustrates the process of the automated design of such a platform.

First, the user defines the geometry (e. g., length and width) and the functionalities (e. g., entry and fixing areas) of the platform to be engineered. Subsequently, all data is submitted to the KBE-System. Using the knowledge base and the part building set, the developed algorithm calculates all parameters to generate a 3D CAD model in a CAD system and establishes a connection to that system. Then, data is transferred bidirectionally. The result is an automatically generated 3D CAD model, including the corresponding production drawings, bill of materials and the resulting production costs.

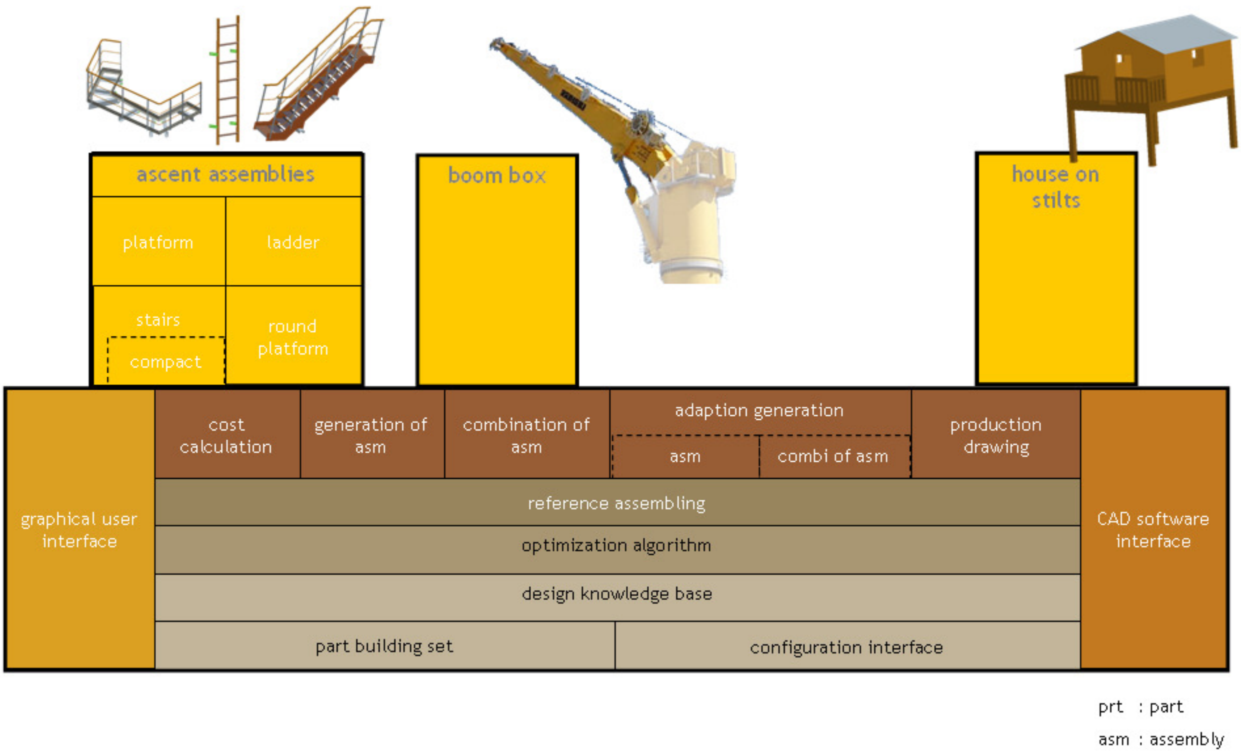

Figure 4. Overview of framework

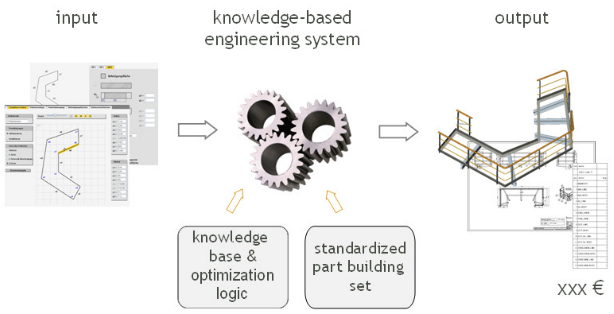

Figure 5. Automatic platform design process

VIII. SUMMARY AND CONCLUSIONS

For enterprises which operate in markets where customer needs can only be fulfilled by way of highly individualized products (in turn necessitating a high variety of products, assemblies and parts), it is crucial to find ways of reducing design and manufacturing costs. This paper presented a KBE-approach to help solving such challenges.

From the start, the described application was developed towards a generic framework. While the framework was so far mainly used for the business cases of ascent assemblies and boom boxes, it is not limited to these tasks. An adaptation and extension towards other assemblies and components is possible.

All assemblies, the design process of which is based on a repetitive logic, can be generated automatically. Also, if a part set of all necessary parts of an assembly type exists and if the design know-how is modeled in a rule system, a design from scratch is possible.

The main challenge is to identify these processes and determine as well as capture the engineering knowledge they represent. By way of operational use of the presented methodology and KBE-application in its engineering department, LWN gained valuable insight and further builds on this experience in future application areas.

By automating the creation of new assemblies and the adaption of existing ones, the complexity of design processes is well reduced and a significant speed-up is achieved. The engineering of ascent assemblies of an LWN offshore crane used to require up to 150 hours. Employing the here proposed software, these efforts can be cut down to 10 to 20 percent.

These savings in terms of cost and time were realized with the presented application through the following features:

- minimized engineering costs
- integration of structural analysis
- extensive reduction of the engineering period
- production-suitable CAD models (models, characterized by feasible dimensions, tolerances and adequate material attributes for manufacturing them [5])
- reproducibility of all created assemblies
- enabled iterative engineering
- storing the expert knowledge in a rule-base.

IX. ACKNOWLEDGEMENTS

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