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SIMULATION BASED AUTOMATED DESIGN TO COST OF STRUCTURALLY COMPLEX PRODUCTS

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1. Introduction

Companies try to fulfil customer needs. For a manufacturing company this can result in an extensive number of assemblies and parts to cover the specific needs of every custom. Since this approach is very costly regarding development and production, enterprises aim to optimize their costs while still maintaining the possibility to satisfy the customer.
One way to solve this challenge is to limit the offered products to a fix set. In most areas an optimal trade-off between customer demands and internal costs can be found. However, there are certain market segments where the only way to be successful is the adaption of a product to customers needs. An example of such a segment can be seen in certain ship crane markets.
Liebherr-Werk Nenzing (LWN) is a manufacturer of an extensive range of products including ship-, offshore- and harbour mobile cranes as well as hydraulic duty cycle crawler cranes and lift cranes. Its mission is to fulfil customers' needs. While standardization is possible in many of its products, there are also segments that require adaption of the crane to specific market demands. This results in a partially or fully 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 high efforts and contribute 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 a close co-operation with the industrial research centre V-Research in order to analyze possibilities of optimizing the development process and reducing design and production costs.
By investigating the design process of ascent assemblies and boom boxes, we found out 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 modelled and stored. The only exception is the structural analysis of the assemblies. The results showed that the statics of ascent assemblies can be mapped by rules. However, the statics calculations of boom boxes are more complex. To verify static stability of these assemblies, special structural analysis simulation algorithms have to be integrated into the design process.
Furthermore, the current building blocks of the assemblies were analyzed. In doing so we pointed out that a high number of part variants existed, which in turn lead to high costs. To reduce the number of part variants, we proposed to develop a fixed set of standardized parts, which is sufficient to design 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. A software application permits the design of the described assembly types more efficiently.

2. Business cases

LWN defined two assembly types, which served as business cases for our research. These were ascent assemblies and boom boxes. Their design effort and production costs were significantly high.
On the left side of figure 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 image, 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 fulfil specific customer requirements consisting of lifting capacity, 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.

Figure 1. Ascent assemblies and boom box

3. Methodological background

This approach is underpinned by two known methods: Knowledge based engineering and structural analysis. They are shortly defined in the following subsections.

3.1 Knowledge Based Engineering

The core competence of many companies is reflected in their special knowledge of product development. Usually, it is their competitive advantage. Especially in the engineering industry, the design know-how contributes a significant portion of the unique selling proposition. However, this know-how is usually not documented very well, only stored in the heads of a small number of key employees. Hence, loosing one of these persons can have serious impacts on the firm's competitive advantage. Furthermore, a great part of the limited time of key personnel is committed to the transfer of that knowledge to other, especially new, employees. Since some companies like LWN are aware of that problem, a central goal of that approach is to save the companies' specific know-how and to facilitate its transfer.
A known methodology for that purpose is Knowledge Based Engineering (KBE). According to [Stokes 2001], KBE can be defined as:
"The use of advanced software techniques to capture and re-use product and process knowledge in an integrated way."
Concerning the approach of this paper, KBE is based on an IT application with high usability that supplies and processes knowledge and interacts with a CAD system. The result is an automatically generated solution according to the designer's input. The CAD system itself is completed by explicitly

modelled knowledge in form of a programmable application. This knowledge contains all information about a product, i.e. its structure, function and behaviour as well as its manufacturability and quality. This is all the data a designer has to know and to enter into a CAD system.
To use the KBE approach the users' expertise has to be collected 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 [Aziz 2005].
Furthermore KBE is also called expert system. Systems of that type store and accumulate specific knowledge of different areas and generate solutions in a user interface to given problems. For more information see [Steinbichler 2008].

3.2 Structural analysis

In [Horikawa 2009] 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."
The structural analysis aims at ensuring the adequacy of the design according to safety and serviceability of the structure. Its process consists of different sub-processes. Figure illustrates the iterative statics calculations of a product structure.

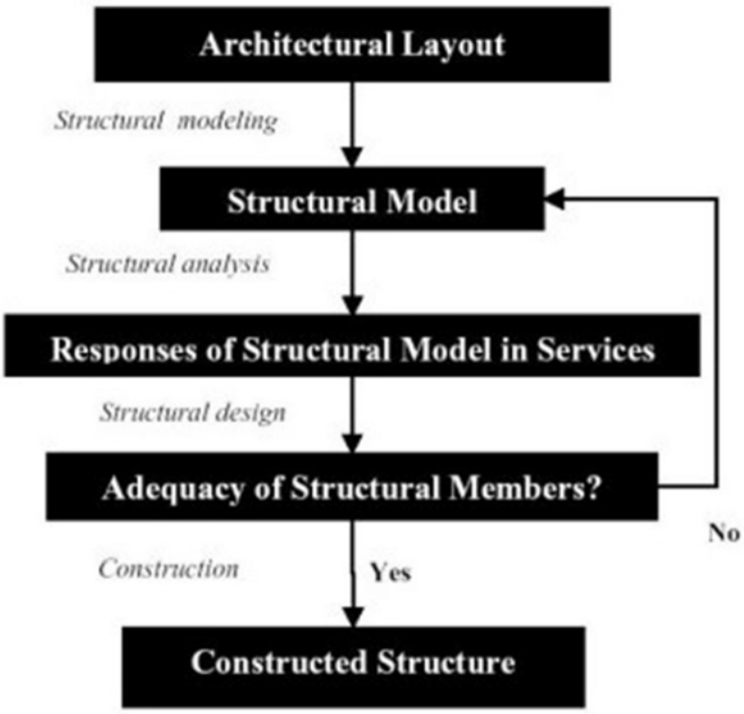

Figure 2. Process of structural analysis [Horikawa 2009]

Usually a structural model is made up of three major components: The structural model, the prescribed excitations and the structural responses as the result of the explained analysis process. To specify the behaviour of a structure, it must be modelled in a set of mathematical equations. The solution of the resulting model provides all necessary information.
We applied the explained methodologies to the business cases defined in the previous section. In the following sections we will present details of our work.

4. Concept of a KBE application

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

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

4.1 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 when designing a platform, these restrictions are special assembly logics or platform entries conforming to standards.

4.2 Modelling of the design knowledge

To build up a KBE system, the engineer expertise has to be collected. Our analysis has shown that engineering processes can be differentiated to 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 modelling them as a system of rules.

In contrast to repetitive processes, creative ones occur typically only ones. Because of that, modelling 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 execute cognitive tasks identically, it is important to support users with a tool (in this case a software application).

To fulfil this goal, and to capture all relevant steps for designing the focused assemblies, we conducted numerous interviews with engineering experts at LWN. The retrieved information served as a base for analyzing the repetitive design processes. The main part of the time spent was used for detecting the restrictions defined in section 4.1.

The obtained data was prepared to be stored as rules in an IT system. These rules represent directed dependencies in the form of IF (condition/-s), THEN (action/-s), i.e. all conditions must be known and must be fulfilled before a rule can be applied [Brinkop 1999].

The rule set can be used for any arbitrary type of assemblies. They can be changed without editing the source code of the software. In addition, if a full range of rules is acquired, nearly every form of an 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 [Adickes 2008].

4.3 Optimization by cost minimization

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 [Krappinger 2008].

All engineering tasks which are not covered by this system, for instance the structural analysis of booms, are optimized by integration of 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.

5. Development of a KBE application

The described approaches are fundamental for the developed KBE system application.
In the following sections the most important components of the application are described.

5.1 Part building set

One of the goals of the realized application was minimizing the number of used parts. This can be achieved by reducing part variety, standardization of parts and limiting the amount of possible production processes. Hence, we defined a restricted set of parts. The created algorithm only utilizes parts of that set which is made up of three distinct classes of parts (see Figure 3):

- library parts
- adjustable library parts and
- parts out of raw material

Library parts are completely fixed. A change is prohibited. The geometry of adjustable library parts is also static, but some dimensions, e. g. the length, can be changed. Raw material parts on the contrary offer the most freedom, as most of their parameters can be adjusted (e.g. a handrail that is bent into a certain shape). Their name originates from the fact that they can be manufactured directly from the stored raw material.
Depending on the requirements of every assembly, the algorithm chooses the adequate parts and, if necessary, adapts dimensions or geometry.

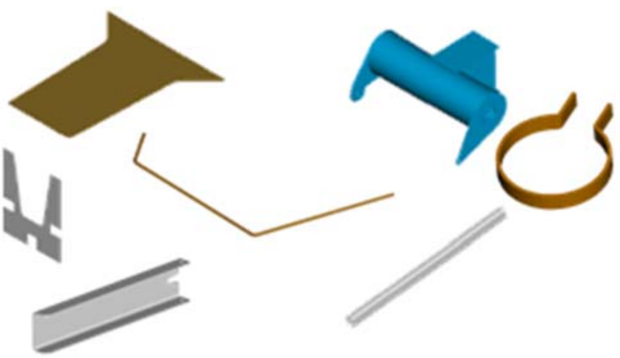

Figure 3. Part building set

5.2 Man-machine interface

Another important component of the developed application is a graphical user interface. This interface is used to interchange data between the user and the algorithm. Our focus was set on minimizing user's inputs. The goal was to allow users to define an assembly as efficiently as possible. Finally, design engineers only have to provide data that cannot be retrieved automatically. Furthermore, they are supported by interactive sketches. Inputs are directly visualized.
Every irregularity corresponding to the defined processes is highlighted by interaction dialogs. For example, if the design engineer defines conflicting data, the application alerts the user.
In addition, the user is supported by some assisting tools. One of these 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).

5.3 Component assembling

Once an assembly is defined by the user, and, if necessary, the structural data is calculated, the respective data is handed over to the automated design to cost algorithm. After calculating all necessary information for generating a 3D CAD model, computed data is sent to a CAD software in an iterative way.
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 the 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.

5.4 Production drawings

To complete the designing process, production drawings have to be generated. As a consequence, the developed application also generates these documents automatically.
In order to efficiently use the available space on the drawing sheets, the positions of all required views are calculated by an algorithm based on trim optimization. To 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 positioned at the best left place.
After all views have been positioned, all production-relevant dimensions or measurements are automatically added by a generic framework. This framework is based on a classification of dimension types. Dimensions can be referenced on:

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

For every mentioned type a special positioning function exists.
Finally, the bill of materials is added to the drawing.

6. Structural analysis 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).

6.1 Structural complexity of boom boxes

From a statical perspective, ascent assemblies and boom boxes are designed to carry load. However, the approach and construction principle differ significantly between the two.
Ascent assemblies contain specific components, which ensure the adequacy of the design according to safety and serviceability of the structure. Based on these parts a limited set of variants with a fixed geometry exists. Because of that, all statically relevant components can be pre-calculated by using suitable software. The resulting parameters, e. g. the maximum load per square millimetre or the maximum gap to the next statical 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 in a boom box are used as structural elements. Because of the specific market segments requirements and LWN's commitment to fulfilling these (i.e. to provide any arbitrary length and load the customer demands for the boom box), their dimensions vary in a wide range 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 any possible dimensions 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.

6.2 Interaction with the structural analysis application

In figure 2 we have shown a standard structural analysis process. 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 factoring in additional factors, a set of load cases is generated.
Based on this input, a simplified model is generated and processed in the structural analysis software (ANSYS). In ANSYS the model is analysed with all the load cases. Based on multiple iterations the defining parameters of the components (e.g. plate thickness) are optimized.
Figure 4 illustrates the results of a stability analysis of a base plate section with a stiffener.

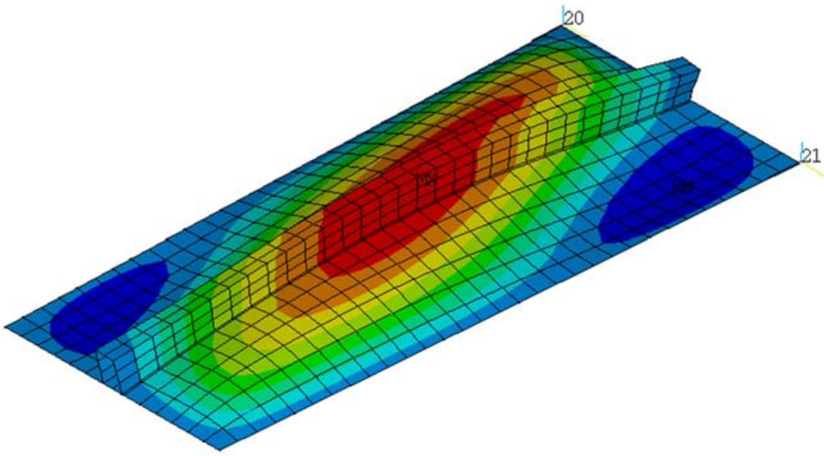

Figure 4. Result of a stability analysis of a base plate section of a boom box

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 this data, the CAD model of the boom can be generated.
As the existing structural analysis procedure is a very time-consuming, complex and labour-intensive process, we tried to simplify and increase the efficiency. We automated nearly all manual activities and integrated it 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 is to define the load cases based on the customer requirements. The developed algorithm then transforms this data into a ANSYS-suitable configuration and transfers it to the structural analysis simulation application. Once the simulation is started, no user interaction is necessary. At the end of the simulation the structural engineer receives all the data to check it.
For returning the results into the KBE system, an additional interface format has been developed.
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 generate a CAD model as described in section 5.
By using this approach, the development process of a structural complex assembly is significantly faster and more effective. This also enables LWN to react quickly to changes in the requirements of the customer.

6.3 Overview developed framework

Figure 5 visualizes all components of the described software. For data exchange, the framework provides several interfaces. These are prepared for assembly independent use. The central brown elements represent the developed algorithm. Since an in-depth explanation of all that modules would go far beyond the extent of this article we dispense with details.
In order to prove the generity of that framework, we tested it by using it for the design of the two explained business cases, ascent assemblies and boom boxes, and houses on stilts.

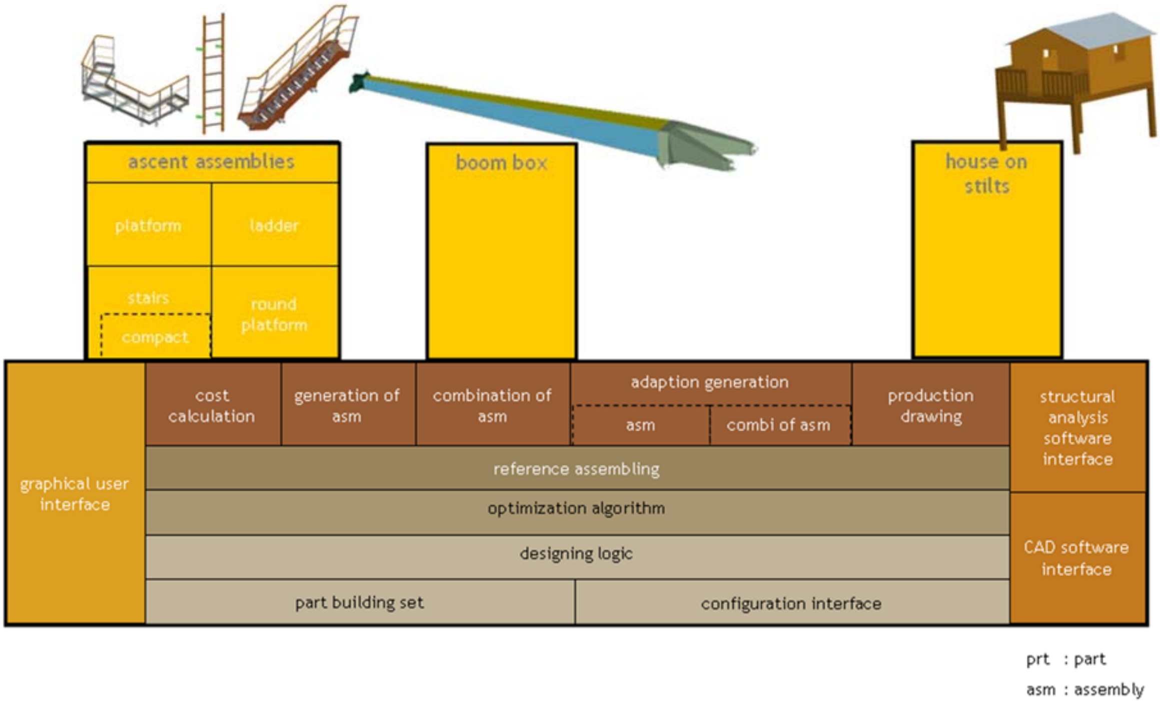

Figure 5. Framework

7. Impacts on engineering and manufacturing processes

The presented KBE system yields a variety of benefits for users. By using the tool, a design engineer only has to determine all the defining parameters of an assembly and fill out the corresponding input fields in the user interface. For example, to generate a ladder, only the length, width, position of the safety cage and the types of fixing elements have to be defined.

Only if a specific design task necessitates deviations from the modelled standards, the engineer has to adapt the resulting CAD model manually. Because the structure of the model is identical to manual designed models, the required non standard, creative decisions can be easily engineered.

Apart from single assemblies, a combination of them can be created as well. This task is supported by a user interface, which provides an assisting wizard that visually and logically aids the user.

Great benefit occurs from the integration of a structural analysis software. Previously, that process was based on regular interaction of an engineer with the software. Now, the only task of an engineer is to check the results. The structural analysis can be run overnight and checked the next morning. This enables the engineer to focus his working time on creative and value creating tasks. In addition to that time-sensitive change, requests can be carried out quickly without binding to many resources. The necessary changes to an already developed CAD model are made by the application itself. For all the defined standard corresponding assemblies, no manual adjustments are necessary.

The software allows developing an assembly iteratively. This means, the engineer can first create an approximate version of the assembly, attach it to the crane, and then adjust it to match the structure.

The application supports the whole designing process: Beginning with the definition of an assembly up to structural analysis, the generation of the 3D model and its drawings (see Figure 6). Even directly after the calculation of the assembly parameters, manufacturing costs are presented in the user interface. The manufacturing costs consist of material, processing and assembling costs.

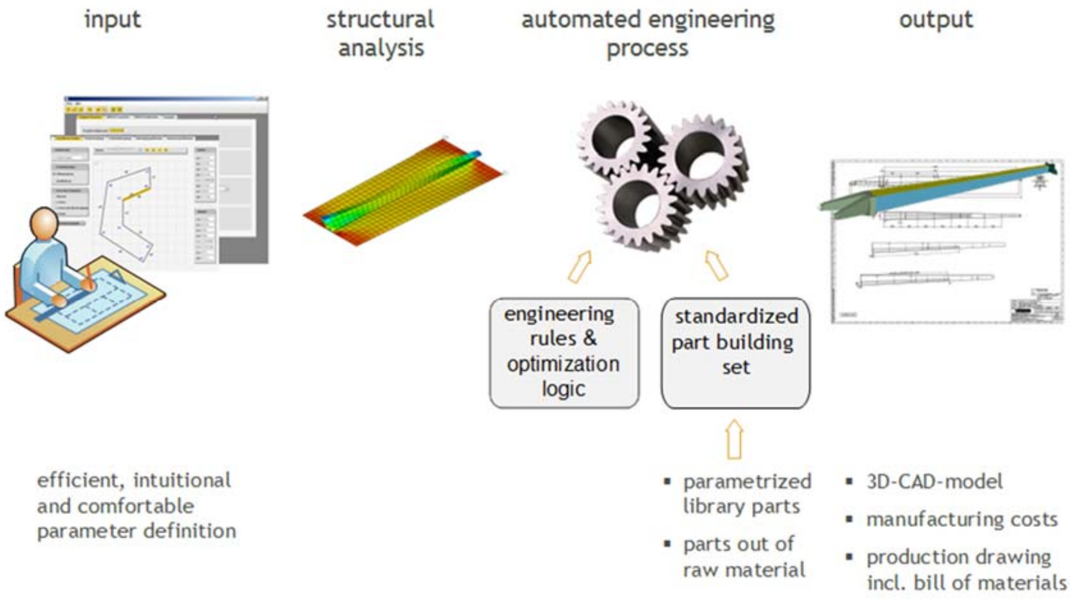

Figure 6. Overview application

Two scenarios exist to apply the application:

- Adaptation engineering: Customer inputs change frequently. The adaption of 3D models and all dependent parameters are very time-consuming. This application allows the user to quickly react on these changing requirements.
- Variant engineering: By using the application, new variants within type series can be created. The developed part building set guarantees that all new variants correspond to the standards of that series and an increase of part variants is avoided. Because of the additional ability of visualizing variants (3D model) and presenting manufacturing costs, the application is a powerful tool for the engineering process.

8. Summary and conclusion

For enterprises that operate in markets where customer needs can only be fulfilled with highly individual and therefore with a high variety of products, assemblies and parts, it is important to find ways of reducing the designing and manufacturing costs. This paper has presented a KBE approach to help solving such challenges.

The described application has been developed based on the idea of a generic framework. While the framework has been developed and extended with the business cases of ascent assemblies and boom boxes, it is not limited to these tasks. An adaptation of other assemblies and components is possible.

All assemblies whose designing process 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 modelled in a system of rules, design from scratch is possible.

The main challenge is to identify these processes and determine and store the engineering knowledge of them. From the operational use of the presented methodology and KBE application in the engineering department, LWN has gained valuable insights and can build on this experience for future application areas.

By automating the creation of new assemblies and the adaption of existing ones, the complexity of design processes is decreased and speeded up significantly. The engineering of ascent assemblies of an LWN offshore crane required up to 150 hours. Using the proposed software, this effort can be reduced to 10 to 20 percent.

These cost and time savings were realised 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 that are characterized by feasible dimensions, tolerances and adequate material attributes for manufacturing them [Brockmeyer2008])
- reproducibility of all created assemblies
- ability of iterative engineering
- storing the experts knowledge

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