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FEATURE-BASED APPROACH FOR THE AUTOMATED SETUP OF ACCURATE, DESIGN ACCOMPANYING FINITE ELEMENT ANALYSES

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1. Introduction

Due to growing demands for high functional integration, efficient material utilization and shorter development time, computer-based simulation techniques, such as FEA (Finite Element Analyses), has become an essential part of the product development process [Müller 2009]. However, an efficient use of simulation requires an early application in the development process. Furthermore, extensive specialist knowledge is a crucial prerequisite to perform reliable and efficient FEA. This knowledge is usually carried by experienced simulation engineers. Due to time constraints, mainly detailed product models are simulated by them in late development phases. Thus, design accompanying FEA are performed too rarely or the simulations are not sufficiently accurate, if they are applied by non-expert simulation users. In order to meet the increasing requirements on product development, the necessary expert knowledge has to be available for less experienced simulation users in design departments. Furthermore, recurring working steps to setup accurate simulations have to be standardized and automated in order to ensure the quality of the computation results and accelerate these processes.

Thus, a knowledge-based FEA assistance system is developed to supports the setup as well as the evaluation of high-quality design-accompanying FEA. The assistance system enables design engineers to early ensure product characteristics and virtually optimize design parameters by reliable structural-mechanical analyses. The necessary knowledge of simulation experts is acquired in a structured and computer-interpretable form by expert interviews as well as by analysing simulation models and simulation reports from already performed and validated FEA. For the analysis of the validated models and reports automated acquisition processes from the area of KDD (Knowledge Discovery in Databases), such as Data and Text Mining, are applied. These automated knowledge acquisition processes and the resulting knowledgebase of the FEA assistance system are described in [Breitsprecher et al. 2015], [Kestel et al. 2015a], [Kestel et al. 2015b], [Kestel et al. 2015c].

The focus of this paper lies on the efficient application of the acquired modelling rules and methods provided in the knowledgebase as well as the automated setup of appropriate FEA on the basis of the existing CAD (Computer-Aided Design) working environment of design engineers. Therefore CAE (Computer-Aided Engineering) features are developed and implemented. According to [VDI 2218], features are defined as the aggregation of geometry elements and/or semantics. The developed CAE features will not only support the design of components or setup of design elements, e.g. CAD features to create threaded holes or chamfers, but also link the CAD representation of components with recurring computation models and methods.

In this paper, a feature-based approach for the automated setup of design-accompanying, accurate FEA and the implementation of appropriate CAE features for nonlinear structural-mechanic analysis of profile construction are described. Following a brief introduction to knowledge-based assistance systems and the previous application of features in the virtual product development, insights are given on the architecture and interfaces of the FEA assistance system. Furthermore, the basic idea of automated acquisition and computer-interpretable representation of simulation knowledge in a knowledgebase is clarified. Against this background, the third chapter describes the potentials and possibilities of CAE features to efficiently provide the acquired modelling rules and methods for design engineers in automated simulation processes. After that, the feature-based approach is demonstrated and evaluated in a use case and finally a summary and outlook are presented.

2. State of the art and background

In the following, the previous application of engineering assistance systems and features used as common data models in the product development is clarified. Furthermore, the current state of the FEA assistance system and the associated acquisition processes to build up an extended knowledgebase for simulation knowledge are presented.

2.1 Knowledge-based assistance systems and common data models

To efficiently apply the acquired simulation knowledge, the FEA assistance system is inspired by the engineering assistance systems mfk and slassy (self-learning engineering assistance system). In accordance to the methods of a design engineer the assistance systems support the product development within synthesis (definition of relevant component characteristics) as well as analysis (determination of component properties and manufacturability) of turned, sheet-metal, casted as well as sheet-bulk metal formed parts [Meerkamm and Hochmuth 1998], [Wartzack 2001], [Breitsprecher and Wartzack 2012]. The exchange of relevant information, such as the diameter for shaft strength calculation, is carried out by CAD features used as common data models. The synthesis and analysis modules of the FEA assistance system refer to the setup of accurate simulations and the evaluation of the results. The exchange of necessary geometry and simulation data between the CAD working environment of design engineers and the simulation environment is also carried out by common data models, the CAE features. The foundations for the use of common data models to couple the CAD and FEA environments and to counteract problems, described in [Peak 2003], regarding the CAD and CAE interoperability and associativity gaps, was laid by [Deng et al. 2002]. A feature was developed incorporating parametric information for both the design and analysis of injection-moulded parts. Further feature-based tools are described in [Zeng et al. 2004], [Shephard et al. 2004], [Lee 2005], [Cao et al. 2009] which support the exchange of models and associated parametric information between CAD and FEA systems. These tools also assist the simplification, defeaturing and decomposition of the transferred models to prepare them for the simulations. The described approaches and tools form the bases of our research. However they are not attached to a comprehensive knowledgebase to provide extensive modelling rules and methods and to automate the context-sensitive setup of accurate simulations.

The common data model proposed in [Gujarathi and Ma 2010] is attached to a knowledgebase and is used to couple the CAD and FEA environments. However, the focus lies on the assistance of design cycles and the application of design knowledge, standardized procedures and regulatory codes. In these design cycles the geometric information as well as basic parameters required for analysis, such as material properties and constraint parameters, are used for both CAD and CAE analysis. But no extended modelling rules or methods are proposed in the knowledgebase to assist the simulation setup. The described, parametrized mid-plane and solid models used to ensure conceptual and detailed designs of a pressure vessel only work for the given composition. If new components or design elements are added to the model, an appropriate, executable simulation is not automatically generated.

2.2 Insights into the FEA assistance system

By means of the FEA assistance system design engineers are enabled to setup accurate simulation models as well as to evaluate the simulation results. The concept of the FEA assistance system was presented in [Kestel et al. 2015c] and Figure 1 shows its architecture and interfaces. As recommended by [Rude 1998] and [VDI-EKV 1992], the assistance system includes a knowledge acquisition component, a knowledgebase as well as a control system, composed of problem-solving, dialogue and explanation components. Through the acquisition component the manual acquisition of simulation knowledge is supported, inter alia, by expert interviews. But these acquisition processes are very time consuming and due to high workloads, simulation engineers are rarely deployable for interviews. Therefore, automated KDD processes are developed and applied to acquire the necessary simulation knowledge. These processes are used to analyse the available models of validated simulations as well as unstructured text-based reports. The problem-solving component is used to evaluate the acquired knowledge for given simulation tasks and requirements and to determine appropriate FEA models by inference mechanisms [Wartzack 2001]. Subsequently, the comprehensibility and traceability of the derived solutions is ensured by the explanation component. The dialog component navigates the user through the modelling process in Pre-Processing and supports the user by interpreting and checking the results for plausibility [Katona et al. 2014], [Spruegel et al. 2015] in Post-Processing. However, mostly in Post-Processing the user interaction takes place in a FEA environment. Since the assistance system is developed for design engineers and has thus to be embedded into their existing working environment, the definition of simulation-relevant parameters, like loads and mountings, mainly has to take place in a CAD system. Hereby increased usability and acceptance is ensured for the assistance system.

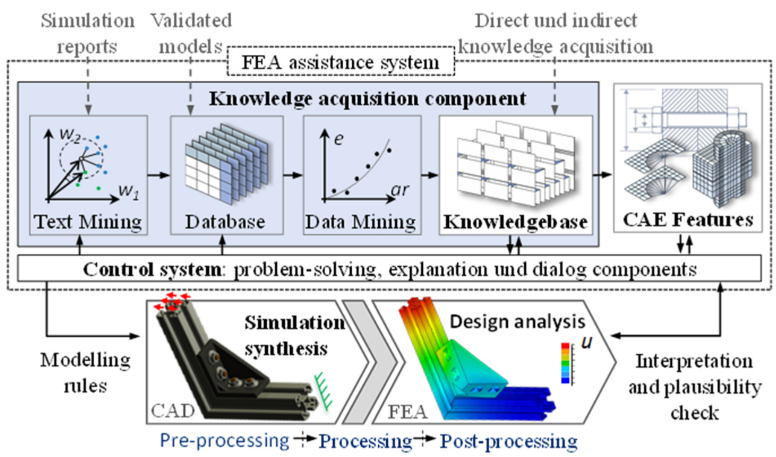

Figure 1. FEA assistance system according to [VDI-EKV 1992], [Rude 1998], [Kestel et al. 2015c]

As already mentioned, CAE features are used to couple the CAD and FEA systems as well as manage the necessary design and simulation parameters. In addition to the CAD representation of a component, recurring simulation models and methods are aggregated in these cross-domain product data models in conjunction with semantic information. By semantic information components and design elements are identified in a model. This way, components and relevant regions can be automatically detected in the FEA systems and specifically prepared for a simulation.

2.3 Automated acquisition and representation of simulation knowledge

To automatically acquire simulation knowledge from validated simulation models and reports which usually include extensive expert knowledge, Data Mining and Text Mining processes are applied. In general the aim of Data Mining is the computer-based identification of patterns and relationships in databases [Fayyad et al. 1996]. The foundations to integrate these processes into the product development were laid by preliminary work regarding the new manufacturing technology sheet-bulk metal forming [Breitsprecher and Wartzack 2012] to acquire design-relevant manufacturing knowledge. Knowledge sources were manufacturing data sets from experimental test series and manufacturing process simulations and the Data Mining results were used to predict specific target values that allow an assessment of the manufacturability, like forming forces necessary to form a designed part. But the databases have to be structured to analyse them by these processes. If numerous validated simulation models are available in a company the appropriate, structured data sets could be directly generated and analysed by appropriate Data Mining processes. However, unstructured text-based simulation reports at first have to be prepared and transferred into such data sets. To automate these steps Text Mining are applied on the reports. So far, Text Mining processes [Weiss 2005], [Heyer et al. 2006] are established in the field of web search engines [Baeza-Yates and Ribeiro-Neto 1999], marketing as well as customer relationship management [Hippner et al. 2001] and are adapted and extended for the aims of our research. More detailed information on the Data and Text Mining processes to acquire simulation knowledge can be found in [Breitsprecher et al. 2015], [Kestel et al. 2015a], [Kestel et al. 2015b], [Kestel et al. 2015c]. Below just the basic idea of acquiring simulation knowledge from validated models by means of Data Mining is presented.

The developed acquisition processes are applied to numerous simulation reports and models of cooperating industrial partners to derive modelling rules as well as relationships in the form of response surfaces to map reliable simulation results depending on the computation models. These response surfaces are used to check the results from following, similar simulations. In addition to the available models and reports of previously performed and validated simulations, parameter studies are an efficient possibility to build up an extensive knowledgebase for the FEA assistance system. These studies are used to derive rules and methods by Data Mining processes, inter alia, about the modelling of screw connections in FEA. In the parameter study shown in Figure 2, the geometry parameters are varied, e.g., the screw dimensions and types (attribute dxP in the data set), as well as the required computation results and regions, like the surface pressures under the bolt head (region C_1 for attribute σ), and boundary conditions, such as the loads (attribute F_y), clamping forces (F_p) and mountings. Furthermore, different mesh and contact settings, required results as well as load cases are defined to the given geometry settings. In Figure 2 these simulation settings relate to the element types (attribute T), e.g. to model a bolt connection with solids or shell and beam elements, and to the contact conditions (C), like bonded, frictional or thread contact, as well as to the element sizes (S). Moreover, the results of the different simulations are compared with analytical solutions or high-detailed simulations as well as with experimental studies to determine the accuracy of the examined models. By these comparisons statements can be made about the effects of the simplifications or about the critical regions of an examined component which need e.g. a finer mesh, like the bolt thread regions. From the considered discrete simulation settings and results general relationships are derived by Data Mining. For example rules are derived in the form of classification trees to decide in which load and application cases the different model variants of a screw connection are suitable (see Figure 2). Examples for the attributes analysed by Data Mining and used as input for the derived classification trees are the applied loadings, contact conditions, achievable accuracies of required results as well as screw dimensions and types. In the case of mostly axial loadings, beam and shell elements with simplified, frictionless contacts can be sufficient to model a screw connection in extensive simulation models. Whereas solid models as well as frictional and thread contacts are required to compute the complete resulting stress distribution within cross-loaded screws connections. Furthermore, the analysed, discrete simulation data is approximated by continuous polynomial regression functions, as shown in Figure 2. In the given regression function, the relationship between the screw dimensions and the suitable cross sections and material properties of beam spare elements is described. By these spare elements the screw connection is model in simplified simulations. Artificial Neural Networks are applied for both regression and classification and can model complex, nonlinear relationships [VDI 3550]. However, in contrast to the previously described classification trees and regression functions the results of Neural Networks are not transparent to the user [VDI 2230], [Tan et al. 2005], [Han et al. 2012].

The meta-models, like the classification trees, resulting from the Data Mining analyses are finally used to predict the appropriate simulation settings for the given geometry, required results as well as load cases. The predicted parameter combinations have not to be included in the previously analysed parameter studies. Furthermore, the prediction accuracy is determined for the meta-models to choose the most suitable meta-models for the given simulation data set. Therefore, a part of the data sets is used as test data and validation methods, such as cross-validation, are applied [Tan et al. 2005], [Han et al. 2012].

The central knowledgebase and control system to provide and process the acquired simulation knowledge is implemented in the object-oriented and web-based SPDM (Simulation Process and Data

Management) system of ANSYS EKM (Engineering Knowledge Manager), as described in [Kestel et al. 2015a], [Kestel et al. 2015b]. Thus, the meta-models derived in the Data Mining environments of RapidMiner and MathWorks MATLAB have to be translated into consistent data structures executable in EKM. These translation processes are automated by scripts implemented in MATLAB. Rule-based meta-models, like classification trees, are provided as conditional statements in the knowledgebase and regression functions are represented as mathematical expressions and relations (constraint-based) [Spur and Krause 1997]. Whereas the analysis results of neural networks or e.g. K-nearest Neighbour classificators, which are not directly representable by rules or equations, are left in their original forms. To process these knowledge contents, tools like RapidMiner are executable as external applications in EKM. Furthermore, the considered components, connection or sub-elements, required in- and output parameters as well as steps and conditions in the development process, in which the rules, equations or meta-models are applied, are attached as additional information (meta data) to the contents in the knowledgebase. Moreover, a user interface is developed to manually acquire knowledge and translate the user input into the described data structures and formats.

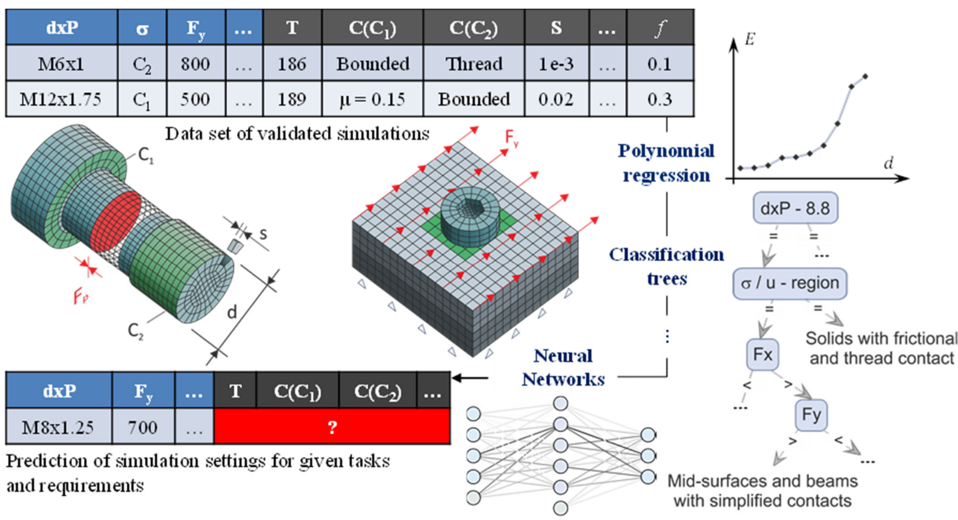

Figure 2. Automated acquisition of simulation knowledge according to [Kestel et al. 2015c]

3. Feature-based knowledge application in automated simulation processes

In this paper, an approach is introduced to apply the described simulation knowledge represented, e.g., by decision trees, curve functions, probability distributions or Neural Networks (see Figure 2) in automated simulation processes starting from the usual working environment of design engineers. Since the existing CAD-integrated FEA tools do not have the full functionality of independent FEA systems usually applied by simulation engineers (like nonlinear simulations with frictional contacts), features are developed to couple common CAD environments with FEA systems established in analysis departments. Previous feature-based approaches described in section 2.1 form the foundations for this research work. However, the state of the art is restricted to the coupling of design and simulation systems and models and the application of design knowledge using features on component level or for predefined assembly structures, e.g., the conceptual and detailed designs of a pressure vessel in [Gujarathi and Ma 2010] or sheet-bulk metal formed parts described in [Breitsprecher and Wartzack 2012]. The issue how individual, extensive simulation processes based on the CAD environment of design engineers can be automated and assisted by comprehensive modelling rules and methods provided in a structured knowledgebase has not been solved yet. Within our research work new methods had to be developed and implemented to provide, process and apply the versatile and context-sensitive (strongly depending on geometry, loadings as well as required results and degree of detail) expert knowledge of simulation engineers. Furthermore, the developed approach addresses the setup and simulation of individual assemblies with variable structures and freely combined components. Thus, the simulation-relevant regions have to be identified and equivalent loadings in specific areas have to be determined in a model that not solely consists of one of the previously analysed components. This is the case, e.g., if in a profile construction (including several bolt connections and sectional beams) the loads and mountings are not applied at the same regions like in the parameter study in Figure 2. Hence, an appropriate feature library is developed as an essential part of the assistance system.

3.1 Requirements and functionality

The simulation setup has to take place in the existing working environment of design engineers. Therefore the design and simulation environments have to be coupled and the functionality of the CAD system has to be extended, e.g. to define the loads and required computation results. Furthermore additional, simulation-relevant geometry elements have to be attached to the feature models, e.g., mid-surfaces or contact surfaces. Moreover, to apply the acquired simulation knowledge in the knowledgebase the considered components, geometry settings, load cases as well as required computation results are needed as input parameters for the prediction models (see data set in Figure 3).

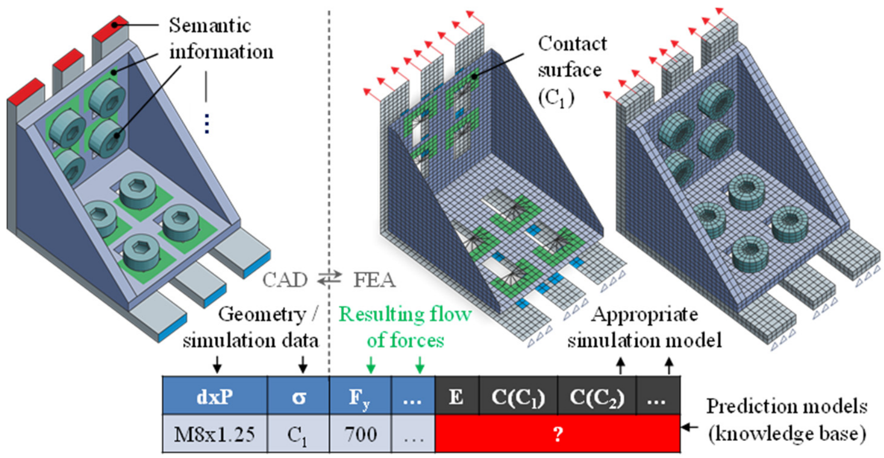

Figure 3. CAD-FEA coupling and evaluation of simulation knowledge

By semantic information these input parameters have to be associated with the CAD and FEA model geometry to be identified by the assistance system, like the bolts and sectional beams as well as contact surfaces in Figure 3 (see model on the left hand-side). The geometry and material settings as well as required computation results (in Figure 3, surface pressure under the bolt head, C_1) are determined in the CAD system. Furthermore, the flow of forces has to be computed in previous simplified simulations consisting of mid-surfaces and rigid connections. This way the forces can be determined, which result at the interfaces of the features. An example for these interfaces is surface C_1 which is identified by semantic information (see second model in Figure 3). In the parameter studies in Figure 2, the loadings are applied to surface C_1 to analyse the bolt connections and create appropriate prediction models, like the classification tree. If the resulting forces in these regions are computed in simplified simulations, the input parameter F_y (see data sets in Figure 2 and 3) can be determined and processed by the meta-models. As a result, appropriate simulation settings are predicted by the meta-models and an accurate simulation model is created automatically using the semantic information, e.g., about the location of components, contact surfaces as well as critical regions (see Figure 3).

3.2 Implementation

The FEA assistance system is implemented in the CAD and FEA systems of PTC Creo Parametric and ANSYS Workbench which are widely established in practice. The implementation of the assistance system in the design environment is carried out in the programming environment of SmartAssembly by extending additional applications (B&W Software) for Creo Parametric: IFX (Intelligent Fastener Extension), used so far for the CAD modelling of screw and pin connections, and AFX (Advanced Framework Extension) for the feature-based design of profile constructions. As already mentioned, the knowledgebase and components of the control system to provide and process the available simulation knowledge are implemented in EKM. Moreover, the simulation processes are automated by using MATLAB, to implement the CAD-FEA-interface, and ANSYS APDL (ANSYS Parametric Design Language) in cooperation with ANSYS Germany. Furthermore, ANSYS ACT (Application Customization Toolkit) is used to implement the user interface of the assistant system in the FEA environment. The focus of research lies on structural-mechanic analyses of bolted and welded steel constructions and the development of appropriate CAE feature libraries. In Figure 4 the assembly consists of CAE features for sectional beams, sheet metal parts, screw connections and welded joints.

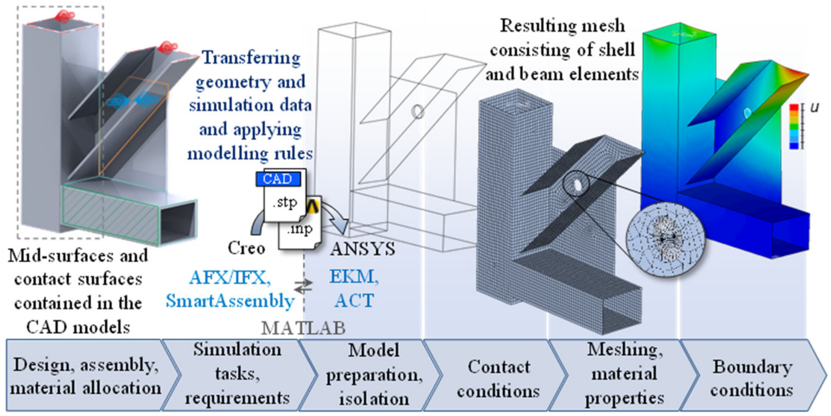

Figure 4. Automated setup of accurate simulation models according to [Kestel et al. 2015c]

The assemblies will be created by using the extended feature library of AFX and IFX and the dimensions of these components are customized in the CAD system by the given geometric parameters. Furthermore, the boundary conditions as well as required computation results will be defined in the design environment and contact surfaces as well as mid-surfaces (for simplified simulations) will be contained in the feature models, using the parametric associativity of the CAD system. As shown in Figure 4, the aim is to transfer the geometry of the assembly as well as given simulation parameters and associated coordinates in a neutral STEP (standard for the exchange of product model data, ISO 10303) file to the CAE system ANSYS. Examples are the preloads, measurements and mid-point coordinates of bolt heads and nuts, the coordinate points, surface normals and assigned components of friction contact pairs, mountings and loadings (see semantic information in Figure 3) as well as the position and offset of mid-surfaces attached and listed in the STEP-file. After that, in conjunction with the related modelling rules and methods, described in section 2.3, executable APDL simulation scripts are generated on basis of the given simulation and geometry information in the STEP file. These simulation scripts are used to automatically create accurate FEA depending on the given tasks and requirements. In Figure 4, the mid-surfaces are linked (welded joints) and meshed by shell elements and the screws are modelled by beam spare elements.

3.3 Case study

To demonstrate and evaluate the presented approach, a case study about the structural-mechanic analysis of a bolted profile construction is performed (see Figure 5). Therefore appropriate CAE features were implemented and the necessary knowledge to setup accurate FEA depending on the task and required degree of detail is provided in the knowledgebase. In this study two load cases with different computation results are simulated, as shown in Figure 5. The sectional beams, profile connector as well as screw connections are inserted as CAE features into the model. By using the efficient CAD functionalities of the additional applications of Creo Parametric, AFX and IFX, the assembly is created and customized in a few steps. Furthermore, by extending these applications, the loads, bolt pretensions and mountings can now be defined in the CAD system and contact and mid-surfaces are already contained in the feature models in Figure 5. The geometry and simulation parameters as well as associated coordinates are transferred in a STEP file to the FEA system. Afterwards an appropriate FEA is created automatically for the profiles, connectors and bolts. The automated simulation setup is based on the determined geometry and simulation parameters in conjunction with the classification trees (to choose the finite element types) and regression functions (to define the dimensions and material properties of beam spare elements) provided in the knowledgebase and shown in Figure 2. For the first load case (see Figure 5) - the previously computed flow of forces is mostly axial - and in order to analyse the bending of sectional beams, the generated model consists of shell and beam elements with simplified, frictionless contacts.

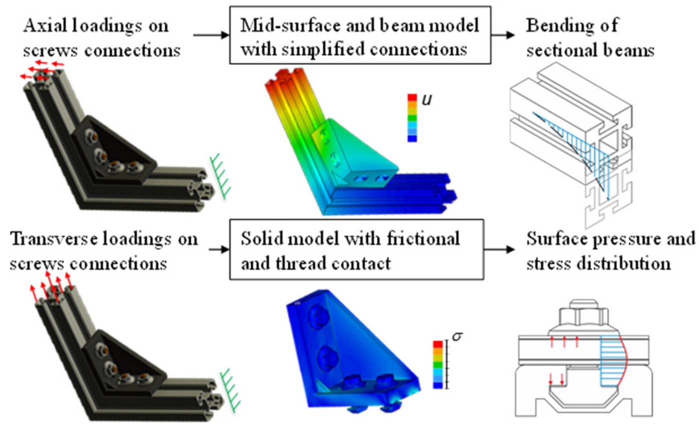

Figure 5. Knowledge-based setup of structural analyses of bolted profile constructions

By modifying the geometry or simulation parameters an appropriate simulation is immediately generated. For the second load case in Figure 5, to analyse the surface pressure under the bolt und nut heads as well as the resulting stress distributions a solid model with frictional and thread contact is created automatically. The simplifications of the first load case regarding the contacts and the model geometry cannot be applied due to the flow of forces and required computation results.
The implemented CAE features applied in the case study form the basis for further feature developments. The following features will be applied to extensive, industrial case studies, like the steel construction which is part of a machine base, shown in Figure 6.

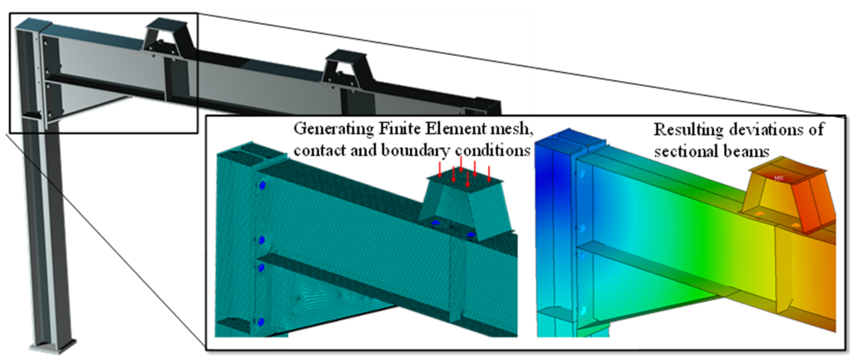

Figure 6. Simulation of a bolted and welded steel construction

The sectional beams, profile connectors and screw connections of this demonstrator are already meshed automatically. But up to now, the welded joints are still modelled manually to run the simulations. These connections have to be modelled with sufficiently smooth transitions since sharp edges in FEA lead to unrealistic stress values (singularities). Furthermore, the gaps which result from the geometry simplification by mid-surfaces have to be closed in these regions [Schmied and Kurmann 2010].
For the evaluation of the assistance system in industrial case studies, the results from the automated simulation processes, applicable by less experienced simulation users, are compared to the results of efficient and reliable FEA previously applied by simulation experts as well as to analytical solutions. Furthermore, in the case of incorrect results, the user is supported by an error assistant to identify and fix the causes and to update the knowledgebase for preventing these errors in following simulations. These Post-processing methods and tools are described in [Spruegel et al. 2015], [Kestel et al. 2015b].

4. Conclusions

The feature-based approach described in this paper is exemplarily implemented for structural-mechanic analyses of bolted and welded profile constructions including sheet metal components, steel beams as well as die-cast aluminium connectors and housings. The potential of these CAE features to couple the CAD and FEA environments, process and apply modelling rules as well as to automate the setup of appropriate simulations was successfully demonstrated in the given case study of a bolted profile construction (see Figure 5). As shown in this example, the expert knowledge provided in a central knowledgebase and applied in these automated simulation processes is not required from the user. Less experienced FEA users in design departments only have to create the CAD models as well as to define the required results, loadings and mountings in their usual design environment.

The presented feature-based approach can also be expanded for the application of further material models, e.g. to simulate the nonlinear behaviour of plastic components, or analyses types, like thermal and acoustic analyses. The integration of additional connection or component types is also conceivable. The applicability of the features is limited to recurring and standardized elements defined by a limited number of configurable geometric parameters. New assemblies are created and automatically prepared for executable simulations by adapting and combining these elements from the feature libraries. Non-feature-based geometry elements can also be added to these assemblies, if they are not influencing critical model regions used by the features, like the contact surfaces or seams edges of feature-based screw and welded connections. These additional geometry elements are still manually prepared by the simulation user. However, in these cases, the user will be supported by modelling instructions context-sensitively provided in the knowledgebase.

The applicability of the automated acquisition processes to capture simulation knowledge from parameter studies and provide it in a structured and computer-interpretable form in a central knowledgebase was also demonstrated for the case study. To show the flexibility and efficiency of the Text and Data Mining processes and enhance these processes, further investigations are carried out by analysing numerous simulation reports and validated models from various industrial use cases.

5. Summary and outlook

Due to increasing requirements in product development, a knowledge-based FEA assistance system is developed to support less experienced simulation users, such as design engineers to early apply efficient high-quality numerical simulations. By this assistance system the necessary knowledge of simulation experts is efficiently acquired and provided computer-interpretable in a structured knowledgebase. To context-sensitively apply the acquired modelling rules and methods as well as to automate the setup of appropriate structural-mechanic analyses based on the existing CAD working environment of design engineers, CAE features are developed and implemented. These features not only support and accelerate the design of components but also link the CAD representation of these components with recurring simulation models and methods. By semantic information the components and relevant model regions are identified by the assistance system and, in conjunction with the related modelling rules, will be specifically prepared for executable, accurate simulations. By the case study presented in this paper (see Figure 5) the potential of the feature-based approach for the application of simulation knowledge and automation of simulation processes was demonstrated. These investigations will be pursued for extended, industrial case studies, like the machine base partially shown in Figure 6.

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