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INTEGRATION OF COMPUTER AIDED DESIGN ANALYSIS INTO THE ENGINEERING DESIGN PROCESS FOR USE BY ENGINEERING DESIGNERS

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ABSTRACT

When developing products, engineering designers often face the problem that their candidate for a technical solution, ranging from a concept to a detailed design, needs to be analyzed by a design analyst before it is approved or rejected and the engineering designer can continue his/her activities within the product development process. If engineering designers have to send every solution candidate to a design analyst, a lot of time and money is lost. To avoid this, some Swedish companies have started to allow their engineering designers to use the analysis capabilities imbedded in modern CAD/CAE software.

In the literature on product development and on computer based design analysis (CBDA) both processes are fairly well described. However, this cannot be said about the interaction between the two processes. This is a growing issue as it represents core knowledge for developing efficient and effective integration concepts, which in turn can be developed into likewise efficient and effective approaches on how to assist the engineering designer to perform parts of the CBDA process on his/her own. Note that when we refer to CBDA here, this is confined to the use of FEM in the development of products, primarily based on working principles originating from the area of Mechanical Engineering.

Since we have been working on a process model for the integration between engineering design and design analysis, this has inspired us to utilize findings from these efforts to propose a conceptual model for a design analysis process driven by the engineering designer to be integrated into the product development process.

The proposed design analysis process model is based on the use of predefined *analysis methods* or *templates*. Templates are also utilized for QA (Quality Assurance) and monitoring of the analysis activities. Responsible for the development of the analysis methods and the templates are expert design analysts,

who develop these tools within a technology development process. Before allowing the engineering designers access to them, these tools need to be approved by relevant bodies within the industrial enterprise and/or by external sources such as those responsible for certification and risk management.

In this paper we present the development of the proposed integrated design analysis process model and an industrial case study, which incorporates a non-linear design analysis activity, utilizing the FEM-program Abaqus within the CAD-software Catia V5 and its imbedded optimization module.

INTRODUCTION

In most product development projects, computer based design analysis, CBDA, or simply design analysis for short, plays an important role for the establishment of the constitutive design parameters of the product-to-be. When we refer to CBDA/design analysis here, focus is put on the establishment of the structural, mainly the mechanical, properties of the product-to-be. This, in practice, restricts the scope of this paper to the utilization of FEM-based analysis tools. In the majority of product development projects, costs as well as increased effectiveness and efficiency are important factors for a successful outcome of the project. For example, by utilizing design analysis, the prototyping costs might decrease due to the need for fewer prototypes. If design analysis can be incorporated into the engineering designer's activities, it will substantially increase the possibility for the engineering designer to explore the available design solution space in a given project on his/her own and thus become more or less independent of a design analyst for quantitative evaluation of product concepts down to detailed design solutions.

During the development of a new concept or detailed design solution, there are usually a number of consultations between the engineering designer and the design analysts. After each of these consultations there is most frequently a need for an adjustment of the concept or the detail. A proposal for a change in the design is most frequently given by the design analyst to the engineering designer, who decides whether to implement the proposal or not or perhaps even create a new solution candidate which might result in additional consultations with the analyst. The number of consultations can be quite large for high-technological products. For example, at Haldex, a Swedish company specialized in brake products and brake components for heavy trucks, trailers and buses, the largest part of the disc brake, the caliper, can undergo 70-100 consultations between various departments, most of them between the design analysis department and the design department, see [1].

Since the responsibilities of the engineering designer and the design analyst are traditionally separated in industrial practice, the communication between the two is often a source of misunderstandings, delays and, even worse, of less robust and reliable designs. It is therefore important to improve communication and understanding by appropriately integrating the design analysis activities into the product development process. In order to facilitate this improvement in the integration of engineering design and design analysis, a proposal for allowing the engineering designer to take over parts of design analysis activities is presented here.

The development of new built-in features in current CAD/CAE software provides new opportunities for engineering designers; now these tools are no longer confined to the creation of the product geometry but also provide the means for design analysis, Knowledge Ware and design optimization.

As the engineering designer is traditionally responsible for generating the technical solution of the entire product and/or of parts of it, he/she has expert knowledge of the functionality of the product and its parts and of most of the external conditions and constraints which will be imposed on the product-to-be. Regardless of the engineering designer's expert knowledge, this does not mean that he/she has all the skills necessary to perform the design analysis on his/her own – even if we assume that the engineering designer has some insights into FEA (Finite Element Analysis). By providing analysis methods/templates for QA and monitoring of the design analysis activities, it is possible to allow the engineering designer to perform at least parts of the design analyses. Note that this implies that the design analyses are to some extent confined to "standardized" analyses, so non-standardized design analyses must remain the responsibility of a design analyst expert.

In this paper, we describe the development of the integrated design analysis procedure model as well as an application example project from industry.

POINT OF DEPARTURE

The proposed integration concept is supported by a number of Swedish companies who want to broaden their use of design analyses, thus planning for the integration of design analysis into the engineering design activity to be partly performed by engineering designers. One of the major obstacles in industry to design analysis performed by engineering designers, has been the QA aspect as well as the monitoring of the design analysis activities.

From a research project aiming at the development of an integrated engineering design and design analysis process model we have been inspired to initiate the development of the current design analysis process model. In preparation for this project, an extensive literature survey was carried out. The result obtained from this survey (covering engineering design, product development and CBDA literature sources) clearly showed the lack of an operationally oriented integration process model. Regardless of the access to such an integrated process model in the literature, industry is handling these issues on a daily basis. Therefore, another survey was done in a number of

Swedish manufacturing companies with in-house CBDA resources and consultants providing CBDA to industry. In this industry survey we found a number of companies using predefined analysis methods to secure the QA aspect as well as monitor the design analyses, and these findings have been our main source of inspiration and support for the proposed analysis concept.

In a recently finished project for a major Swedish truck company, it has been proven that the problems associated with QA and monitoring can be solved with the use of templates. These templates are developed in a separate process, a Technology Development process, by expert design analysts and verified and validated in an industrial setting, [2].

Finally, by utilizing some of the results obtained from the research project mentioned previously, it is possible to understand which factors are of importance for the integration of CBDA into the product development and thus for the engineering design process [3]. In Figure 1, the task clarification steps necessary for setting up a design analysis project are presented, see [4].

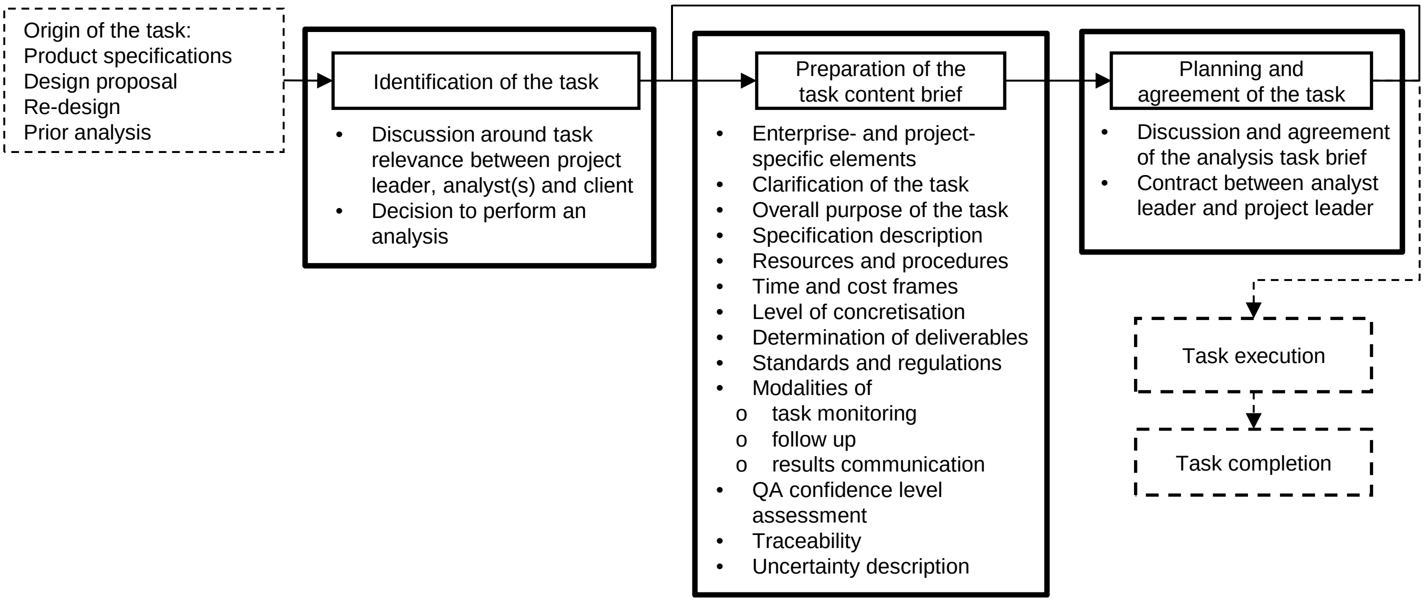

Figure 1. Analysis task clarification steps [4].

The analysis task clarification steps shows how information obtained from the engineering design process is utilized in an enhanced design analysis process model that implements several QA aspects such as QC (Quality Check), V&V (Verification & Validation) and uncertainties, allowing for a better integration of the design analysis activity in the overall engineering design process. Note that the design specifications need to be translated into analysis objectives useable as target values inside the CAD/CAE software, and measures for QA must be set [5].

In order to provide the theoretical foundation upon which the proposed design analysis process model is developed, the following “elements” should be elaborated upon: the engineering design process, the CBDA/design analysis process, process integration, development of the analysis methods/ templates and software integration.

The Engineering Design Process

Within the field of engineering design a large number of publications are available, ranging from research on engineering design processes, design methodology, and specific design methods and techniques to generic engineering design models describing the context in which the engineering design methodologies are to be used. In most of the literature on engineering design, the process is divided into different decision gates, phases, design activities and steps depending on the author, but also on country of origin, “design culture”, in which the process is developed [6-9].

Figure 2 shows a simplified engineering design process model adapted to the level of concretization necessary for the understanding of design activities primarily involved in the integration issues between the engineering design and the design analysis activities.

The simplified process includes the following phases:

- **Specifications**: Assignment of measurable product specifications as a basis for the subsequent concept generation and concept evaluation.
- **Concept Design**: Generation of concept candidates and evaluation and selection of final concept.
- **Embodiment Design:** Establishment of product architecture and design of subsystems and major components.
- **Detailed Design:** Shape and form of individual parts and details including establishment of dimensions, selection of materials etc. A complete set of drawings are also to be included for the manufacturing of α prototype.
- **Verification &Testing**: The α prototype is tested with reference to the product specifications set out for the product-to-be.

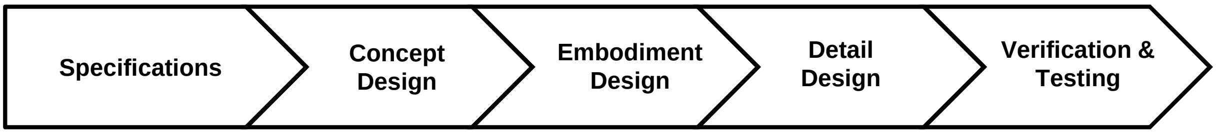

Figure 2.The simplified product development process model.

The CBDA/Design Analysis Process

The design analysis process is generally described in the literature in terms of a number of steps to be taken in order to find a solution to the analysis problem. Numerous publications are available within the field and include research on fundamental design analysis methodology and recommendations on the use of specific purposes for generic design analysis process models, describing how the analysis methodologies are to be used. Previously, when analysis methods such as FEM were less widely diffused, the procedures describing their use in design analysis focused on solving the established numerical problem accurately and efficiently with a number of developed and outlined techniques and methods.

Such procedures can be found in works such as [10;11], to mention just a few within the area of design analysis. These procedures and methods became a very important part in the future development of the techniques. With the further development of software and simplified use of such analysis methods, process models have been eventually developed that include industrial aspects in order to support the practioner's actual design activities. NAFEMS (the National Agency for Finite Element Methods and Standards) in recent decades has proposed several process models that support the practitioner in his/her activities. In *How to plan an FEA*, [12], the workflow of design analysis tasks is extended to include steps that couple analysis to the design or development project.

In [13] the importance of establishing a clearly defined goal and of determining the level of uncertainty of the technical specifications is given special attention.

Other motives are the yields provided by decrease in time and resources, the possibility to introduce a coupled expert system, etc. In [2], a computer-based design system for lightweight grippers has been developed that can be used by production engineers with very limited knowledge of design and design analysis. The grippers are optimized through a simulated annealing algorithm and analyzed using FEM; the system is completely integrated into Catia V5®. In such cases, the synthesis and analysis activities are partly automated, and the “design work” is shifted towards the development of adequate software.

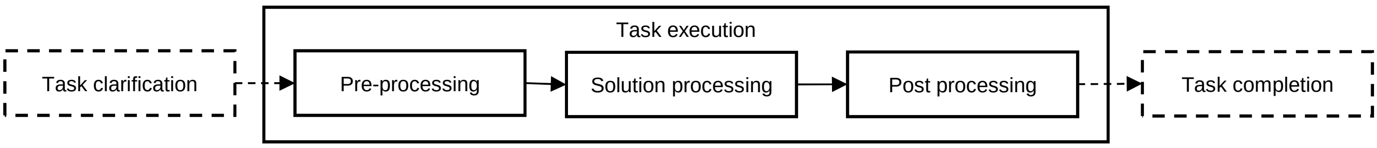

Figure 3. Overall design analysis process model taken from [4]

As a result of the research project on the integration between engineering design and design analysis mentioned previously, the complete design analysis process model is described briefly in Figure 3,[4]. This process model is utilized in the analysis model presented here. Each step includes important activities:

- **Task Clarification:** Agreement on the task, consisting of detailed planning of the analysis task.
- **Pre-Processing:** Preparing and setting up the computational model.
- **Solution processing:** Analysis execution.
- **Post-Processing:** Results verification and accuracy assessment.
- **Task completion:** Interpreting and evaluating the established results and hand it over to the project.

PROCESS INTEGRATION

Effective integration can be tackled in different ways. King et al. [14] have presented a framework (or 'good practice model') for the implementation of FEA and related computer-aided engineering (CAE) into the product development process. They state that effective integration is dependent upon 1) the organization of the product development process, 2) software, 3) hardware, 4) support structures for effective use of CAE in the product development process and 5) product data management.

The process models previously described fulfill these "criteria" and are thus accepted as the necessary constituent elements of the integrated analysis process to be presented here. As was mentioned earlier, it is important to emphasize once again the prerequisite that the engineering designers have none or limited knowledge of design analysis, which demands that all actions should be monitored and the quality of the actions taken be secured by the system. In order to accommodate these analysis methods/templates will provide the necessary means for accomplishing this.

Development of the analysis methods and templates

If we want to allow a non-expert, the engineering designer, to perform design analysis as described above, it is necessary to develop *analysis methods/templates* to support this activity. These methods/templates must be developed by expert design analysts and approved by the industrial enterprise and/or by external bodies such as those responsible for certification and risk management.

The actual analysis methods/templates should be in the form of straight-forward steps to be followed by the engineering designer, thus reducing the risk for mistakes and misunderstandings of the actual analysis procedure.

To be able to secure the QA and to make sure that the engineering designer only takes the steps he/she is allowed to take, templates are utilized for the monitoring of the analysis actions. These templates are developed by expert design analysts and, like the analysis methods, approved by the industrial enterprise and/or externally.

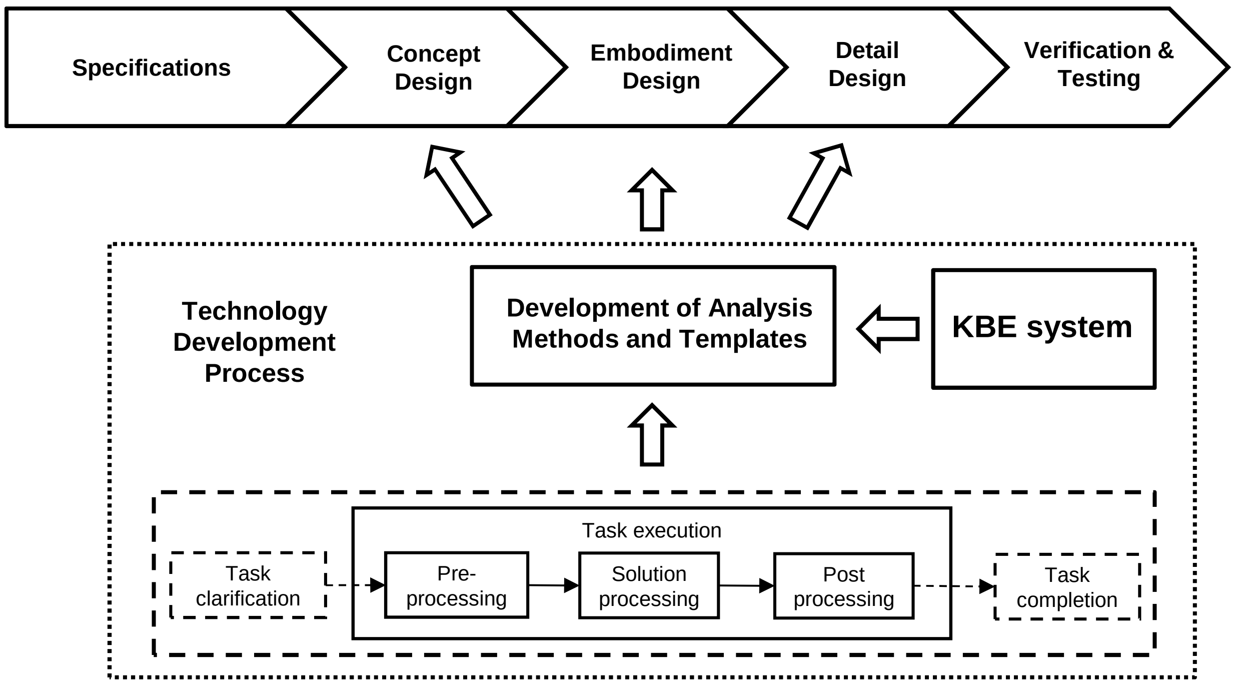

Figure 4. Schematic process model for the integrated design analysis process model.

The analysis methods/templates are all developed within a Technology Development process, which is carried out separately from the daily activities within engineering design and product development in the industrial enterprise.

The complete integrated design analysis process model is illustrated in Figure 4. Note that this model also includes a KBE system (Knowledge Based Engineering system). This is primarily used for capturing experiences from industrial practice in engineering design and analysis activities as well as monitoring and securing the quality of the activities performed. Furthermore, also note that information in the form of specifications (regarding both product and process) are utilized as input in this development activity.

SOFTWARE INTEGRATION

The actual integration is based on an integrated CAD/CAE-System; here the Dassault Systemes© Catia V5© has been used. Regarding the software integration issue, a number of authors have contributed to that area as well as have software developers. In [2;15] integrated CAD/CAE is employed for optimizing products by using design analysis and KBE. Using KBE is only one of many advantages that CAD/CAE integrated software offers. In [2] a design system is built with all the features available from inside the same software, in this case the Catia V5; [16] states that computer support should be *cooperative*, *subordinate*, *flexible* and *useful*. One of the problems when exporting geometry from CAD software to analysis software is that the connection to the original geometry is lost.

Another problem arises if there are errors in the exported geometry; the analysis expert must repair it within the analysis software. There can also be problems with the geometry, problems that the engineering designer did not think about when creating the geometry, for example small holes, small radius and other geometry that is not necessary for the analysis.

Making geometry that suits all kinds of usage demands high skill from the designer, but it is easy to solve. By using different configurations controlled by a parameter, the designer can activate and deactivate geometrical features simply by changing the value of a parameter. Other parameters can control dimensions of sketches and features and be used for optimization. After each of the consultations in the optimization process, the controlled parameter value is changed and the original geometry is automatically updated. Numerous publications have focused on this software integration at diverse levels: interoperability at feature level —CAD to CAE feature simplification and idealization [1;17], CAE to CAD reconstruction [18;19], new shape representation [20] at a higher-information-level [21;22] or complete integration in software packages such as PTC®'s Creo® Parametric ANSYS® Workbench environment, Simulate®, Dassault Systems®' Catia® and Simulia® etc. The integrated design analysis process and its architecture are presented in Figure 5.

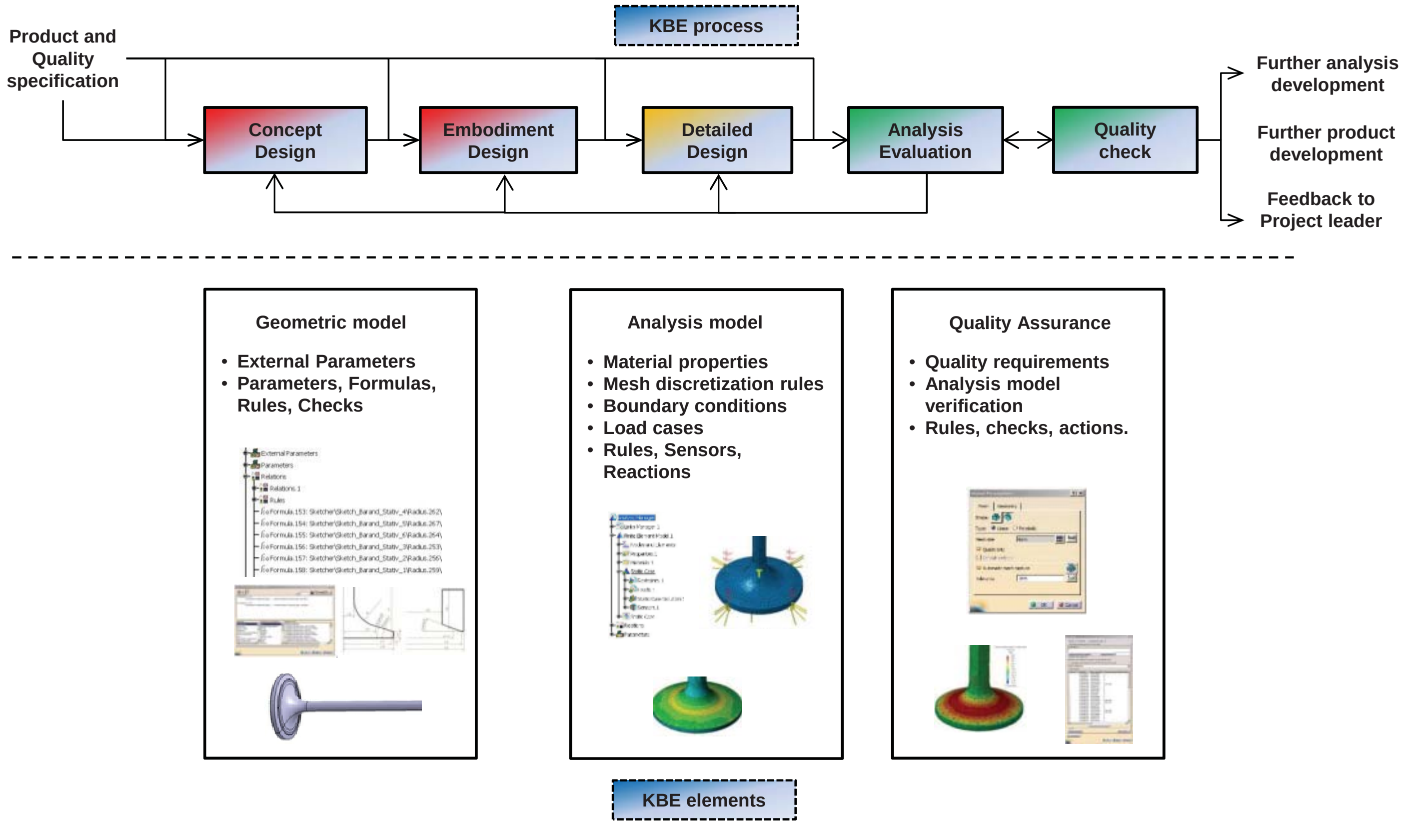

Figure 5. Integration of the process and its architecture(adapted from [2]).

INDUSTRIAL CASE

In this industrial project we set up two different goals. First, we wanted to verify and, if possible, to validate the design analysis concept. In this study, we especially focused on the development of templates and on studying how they were used as a link between product development and design analysis. A second goal was to find out if there are any differences between the FEM workbench GPS/GAS (imbedded in Catia V5), and Abaqus for Catia (a plug-in for Catia V5) in terms of capabilities and handling as well as in terms of integration with other Catia V5 workbenches, for example KBE and the Product Engineering Optimizer (PEO).

In this case, an exhaust valve and its seating for a truck engine have been used for the case study. Since it was decided to optimize the exhaust valve and its seating, the optimization and design analysis execution was expected to be rather time consuming. In addition to the execution itself, time spent for on the built-in features for QA and KBE also helps prolong the total analysis time. For these reasons a simple geometry, like the exhaust valve and its seating, was a perfect choice for the project. Note that in this case templates are utilized to accommodate a *fully automated* design analysis activity.

The project was carried out by five teams of senior engineering design students. These teams worked independently of each other under the supervision of an expert design analyst from the truck manufacturer and the supervisor at the university (the main author). In parallel to the project carried out by the students, a professional engineering designer and expert design analyst carried out the same project, but in the latter case in the "traditional" manner – consultations between the engineering design and the design analyst.

GEOMETRICAL MODEL

Building complex geometrical models and handling all the elements to be integrated, it is important to have an opened geometric model. All dimensions that are affected by the analysis or KBE have to be parameterized. Figures 6 show the first step in setting up the model, parameterizing and connecting it to the dimensions. The solids are parameterized, and the model is controlled and monitored by a set of formulas, checks and rules. A system of checks has been implemented to monitor the integrity of the geometry and dimension specification after changes. This also makes the design system more robust.

Using a Visual Basic script has enhanced user ability in this model. As this integration of design analysis is made by using templates, and as it is important to make sure that the user does not use values outside the allowed values; a dialog box is used as an input. Behind the dialog box, rules are checking the values, and if the values are not inside the accepted parameters, the rules can give a warning or refuse to accept incorrect values. Figure 7 is a picture of the user Visual Basic interface. In the dialog box the user can see all parameters and what dimension each parameter controls. Parameters for the optimization are also set in this dialog box. When all parameters are set; there are two buttons for applying the values to the model.

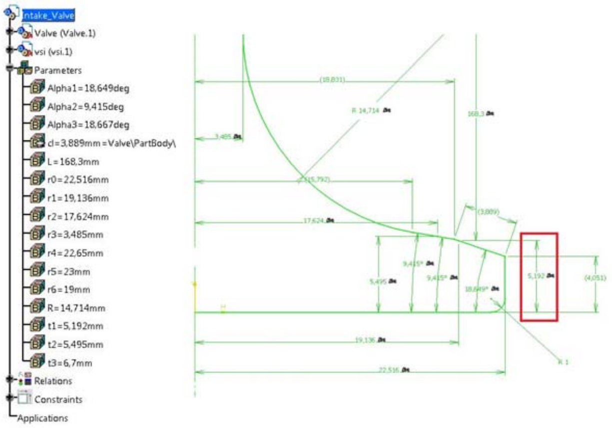

Figure 6. Parameterizing and connecting to the dimensions

In the model used for this project, the geometry of the valve (the contact between the valve and the seating) can change so that the pressure applied affects the model negatively. To be able to ensure that the pressure is always applied correctly, a rule was created checking so that when the dimensions are outside the allowed values the pressure is deactivated. This rule could only be used inside GPS/GAS as a contact connection inside AFC is not parameterized, and it is not possible to activate/deactivate this feature through a rule.

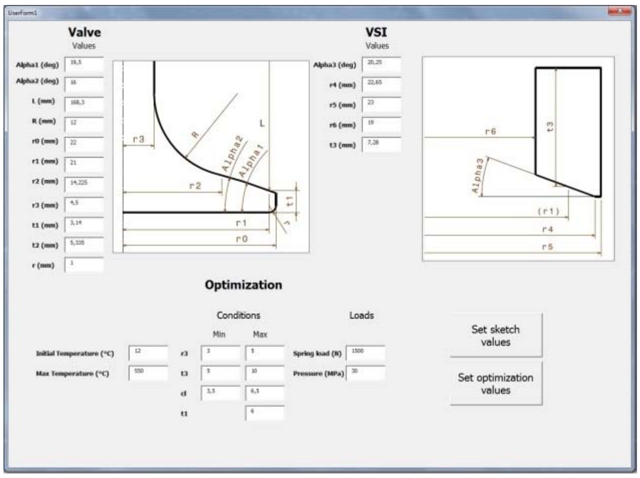

Figure 7. Visual Basic User Interface.

ANALYSIS MODEL

The analysis model contains information about the material properties, boundary conditions and load cases. It also contains mesh discretization rules [17]. For the optimization step, coarse mesh is used: element size 4 mm, 1st order (linear) element, and geometric representation within 0.2 mm. For an improved geometric representation, 2nd order (parabolic) element is used. Depending on the order and quality of the elements, different amounts of time are required to solve the problem.

Quality assurance

Finally, a quality check and verification of the final results is performed. The quality check consists in a mesh convergence study, element quality control, and reaction force summary, together with the assessment of the design system assumptions. Once this final analysis is performed, the results are handed over to an analyst for final assessment of the confidence in the performed analyses and established results.

Geometric model instantiation

The geometric model instantiation is the first step of the part's geometrical design and aims at generating a first geometry.

The values from the user input interface are assigned to the geometric model, and the model is automatically updated; the KBE checks that all dimensions are within the allowed values. As all dimensions are set and the geometrical model is up to date, the engineering designer does not have to manipulate the geometry.

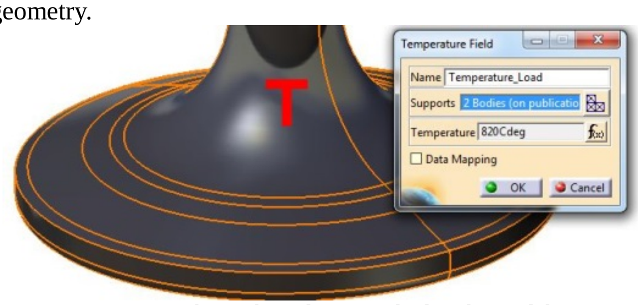

Figure 8. Thermal condition applied to the model.

Analysis model instantiation

An analysis model is then built up with solid element mesh on each part with assigned physical properties. Contact connection is created and a friction coefficient is assigned for the specific material of the models. We also have to set up parameters for the thermal analysis; see Figure 8.

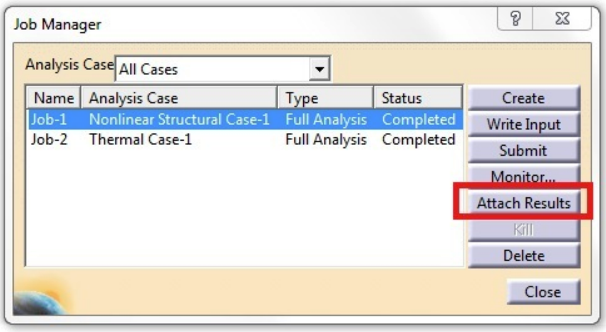

Figure 9. Thermal result attatchment.

There is a difference in when to apply this in AFC and GAS/GPS. Setting up the environment is no major difference, but in AFC the thermal analysis must be made before the static analysis; see Figure 9. When the results from the thermal analysis are available, we start the static analysis and add the previous results from the thermal analysis. A first calculation of the model is performed with the objective of applying all the required input to the subsequent optimization.

After solving the model, the stress and deformation results needed for the optimization are automatically available through the sensors. The user does not need to carry out any action for this step regarding the evaluation of the model.

Optimization

Once a first analysis model is instantiated, the optimization features are introduced. These elements consist of free parameters, constraints and target values. The free parameters are those that the optimization system can change. In our problem, these are the cross sections, thicknesses and diameters of the beam elements of the gripper base. The constraints are those given by the specification and by the material mechanical properties. The target value (optimization function) is to minimize the stresses. During this optimization process it is possible to monitor the progress and to interrupt it. After the completion of the optimization, all calculated values are available in a spreadsheet.

The optimization algorithm used in the PEO of Knowledge Ware is a simulated annealing algorithm whose details are described in [23]. The algorithm parameters (such as stress) are controlled by Catia V5. Between 30 and 90 iterations are usually needed to optimize the model, which amounts to about 2 to 12 hours of solving time.

Result

In this project, design analysis was integrated into the engineering design process. Five different groups of students have, independently of each other, successfully implemented templates and KBE and performed the design analyses. From the outcome of this case, it is clear that the use of templates and implementation of selected design parameters, target values and the setup of the design optimization was suitable for the proposed design analysis concept. The integration works well and the engineer evaluates concepts faster. The work is less time–consuming, and misunderstandings or loss of information are avoided as the engineer performs the design analysis on his/her own. As the integrated developed technology governs the process with the help of the KBE, it is not possible for the designer to set values or for the software to produce results outside these limitations. By implementing Visual Basic (see Figure 7) the potential to make mistakes or to enter the wrong value has been further reduced.

DISCUSSION AND CONCLUSION

In this project, design analysis has been integrated into the engineering design process. This integration has both advantages and disadvantages. A summary of these is listed below:

- Since it is the designer who performs both design and analysis, the work can be carried out directly when needed, eliminating any deficiencies or misconceptions in the exchange of information that might occur when an analysis performance is handed over from the designer to the design analyst.

- The designer can perform evaluations of a concept or a detail early on in a design phase and thus be able to eliminate a large number of candidates without the involvement of the analysis department; the work can be focused on the concepts/details that are better suited for the design solutions.
- The lead time for developing new products can be significantly shortened as the designer can perform design analysis directly when needed instead of having the work sent to the analysis department to be completed when they have the time [24].
- Designers' knowledge of analysis may be limited, which means that clear instructions / procedures on how the tool is to be used must be developed.
- The designer may, in some cases, need the assistance of an expert design analyst when analyses are carried out, when interpreting the results and when unexpected difficulties occur during the analysis.
- The introduction of analysis methods/templates, supported by KBE and developed by design experts or design analysts during a Technology Development process has proven to be a successful concept for facilitating design analysis performed by non-expert design analysts.
- The extensive use of templates makes it possible to monitor and secure the quality of the design analysis project.

The integration of the engineering design and design analysis activities has been both tested and validated in 3 different projects, that is, 2 other projects beside the one reported here. In [2], a computer based design system for lightweight grippers has been developed that can be used by production engineers with very limited knowledge of design and analysis. Finally in [25] a CBDA system had been developed supporting the design and analysis of a bracket for the intercooler system in a truck engine. In this project the validation of the optimization has been carried out together with the company's analysis experts utilizing an external software denoted Inspire [25].

The result from the industrial case also shows that, even though both GPS/GAS and AFC (Abacus for Catia) are imbedded in the Catia V5 environment, there are advantages and disadvantages associated with the use of both softwares.

- GPS/GAS is a FEM program confined to linear analysis and also limited regarding analysis of contact problems and advanced analysis.
- AFC has technology from Abaqus© and has the advantage of its capability of non-linear analysis both in contact (more options) and multi-physic analysis, and is preferred in advanced analyses.
- Comparing the analysis result from GPS/GAS and AFC it was concluded, when analyzing contact with small deformation and thermal, there was no significant difference.
- GPS/GAS has been part of Catia V5 from the beginning and is more integrated in the V5 environment than AFC, which appeared when functions within KBE and PEO were to be used.

In conclusion, both softwares are powerful and easy to use, and it is important that the user have basic knowledge of design analysis. Furthermore, by integrating analysis into the engineering design process and by using GPS/GAS or AFC, all activities are made on the same CAD model, no geometrical or parametric information is lost and all changes are updated to the CAD model directly. The proposed design analysis concept has so many advantages that the truck company immediately after having finished the industrial project accounted for above, decided to proceed in adopting this concept for all of their engineering designers. This implementation project has already started and the actual implementation is planned for late 2013.

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