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A MULTIDISCIPLINARY DESIGN TOOL WITH DOWNSTREAM PROCESSES EMBEDDED FOR CONCEPTUAL DESIGN AND EVALUATION

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Abstract

The actual product ownership often remains with the manufacturer as functional (total care) products emerge in aerospace business agreements. The business risk is then transferred to the manufacturer why downstream knowledge needs to be available in the concept phase to consider all product life cycle aspects. The aim of this work is to study how a multidisciplinary design tool can be used to embed downstream processes for conceptual design and evaluation allowing simulation of life cycle properties. A knowledge enabled engineering approach was used to capture the engineering activities for design and evaluation of jet engine component flanges. For every design change, cost of manufacturing operations, maintenance and performance aspects can be directly assessed. The design tool assures that the engineering activities are performed accordingly to company design specification which creates a better control over the process quality. It also creates a better understanding enabling the engineers to optimize the concept in real time from an overall product life cycle view. The new tool will be the base for optimize the total product system and will be used not only between companies but also between product development departments in large global companies.

Keywords: Knowledge enabled engineering, product life cycle, design support, cost estimation

1 Introduction

The actual product ownership often remains with the manufacturer as functional (total care) product emerges in aerospace business agreements, [1]. As the ownership of jet engines remains with the manufacturer the risk of the business agreement taken increases on the expense of the manufacturer. A jet engine life cycle stretches over a time span of 30 to 40 years and the cost of producing the engine is low compared to the cost of ownership. Early design decisions are often done on scarce information basis as knowledge of activities performed later in the process (downstream knowledge) often is missing in the early engineering design stage. Jet engines owned by the manufacturer will need to be competitive during the entire product life cycle why downstream knowledge needs to be available early.

Design for X (DFX) [2] research includes Design for Life Cycle (DFLC) which emphasizes that all design goals and related constraints should be considered in the early design stage. In the early engineering design stage requirements and constraints are usually imprecise and incomplete and few support tools exist [3].

A number of support tool modeling techniques exists. One technique, knowledge based engineering (KBE) defined by Stokes [4] as "The use of advanced software techniques to capture and re-use product and process knowledge in an integrated way" has been applied a number of times to model routine engineering tasks. As this technique captures activities normally performed by engineers into a computerized system and allows these activities to be performed fast and precise, an ability to extract knowledge not normally available in early phases is created. Still this technique has mostly been used to capture knowledge from design and manufacturing disciplines. Knowledge from all relevant disciplines is needed to make a valid simulation of the product life-cycle.

The aim of this work is to study how a multidisciplinary design tool can be used to embed downstream processes for conceptual design and evaluation allowing simulation of life cycle properties.

The multidisciplinary design tool presented in this paper shows how downstream activities can be modeled using a Knowledge Enabled Engineering (KEE) approach. As the engineer can change the design and directly assess the life-cycle cost, more knowledge of design decision impact is available than without the design tool.

2 Literature review

The literature review is focused on recent product life cycle modeling work. Concurrent engineering (CE) addresses that all DFX issues need to be considered simultaneously during the design stage [5]. Design conflicts between different DFX issues leads inevitable to trade offs. In the early engineering design stage, requirements and constraints are usually imprecise and incomplete and few support tools exist to support this stage [6]. This is also formulated by Prasad [5] as:

"*Design decisions differ with each new piece of added information, new person, or new issue discovered. Design issues continually change and evolve during every step of the design. This is because design is an open ended problem*."

Recent engineering design support approaches have applied knowledge modeling techniques such as expert systems (ES) [6], design rationale (DR) [7 -8], KBE [9 -11] and case based reasoning (CBR) [12-13]. In the attempts made mostly design and manufacturing is included which is too few disciplines for a life cycle view. These knowledge modeling techniques still hold a potential to incorporate knowledge from more disciplines. Dixon [14] defined knowledge based systems as "*...a special class of computer programs that purport to perform, or assist humans in performing, specified intellectual tasks*." which does not in any way limit the use of these system to a specific discipline. All the knowledge modeling techniques presented above have different advantages depending on what knowledge is of interest to capture. DR, for example, captures how, why and what about design decisions. Why not use the method most suitable for the activity to support? That is the main purpose of the Knowledge Enabled Engineering approach.

3 The Flange Design Process

This section constitutes a short description of the flange design process that was subject to be supported by the tool. A rotational symmetric flange joint (figure 1) have an important function as an interface between jet engine components.

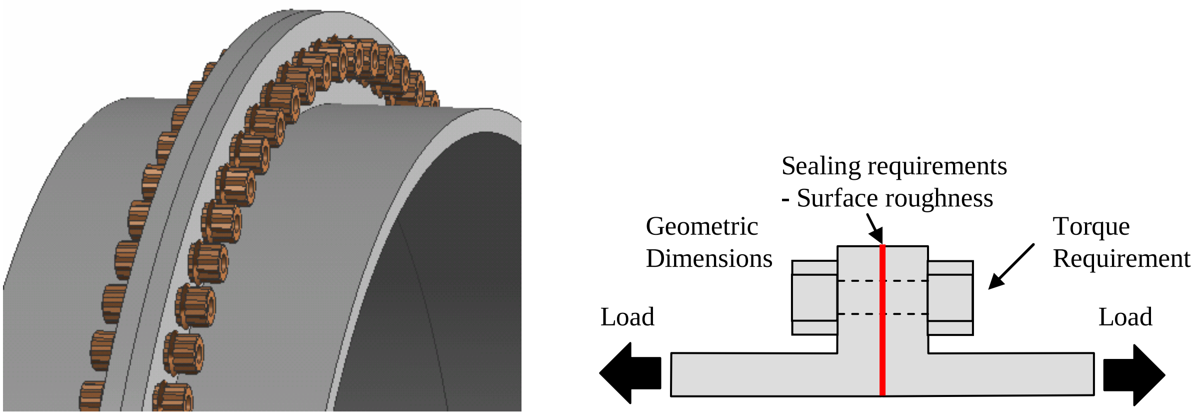

Figure 1. Section of a circular flange where the right picture displays the requirements and loads.

The flange has several functions:

- transferring loads between components
- preventing engine leakage
- allow dismantle and assemble of jet engine components

The flange design process includes performance, manufacturing and maintenance issues that are briefly described below.

3.1 Performance

The first step of the flange design process is finding geometry and bolts that fulfill the load and leakage requirements. The dimensioning process starts by choosing initial values, usually previously used on a similar flange with similar requirements. When the geometry is initially defined it is possible to calculate if the bolt joint will withstand the applied load and prevent leakage.

3.2 Manufacturing

A team of manufacturing engineers, weld technicians and other experts need a geometrical representation to define a manufacturing plan. The team creates an operation list describing each manufacturing operation, including the manufacturing time. A common issue between design and manufacturing engineers are the tolerance requirements. When the tolerances are satisfactory from both a design and a manufacturing point of view the team defines the operation list that later is used in the production process.

3.3 Maintenance

The flange acts as the interface between jet engine components and the design affects the time each maintenance operation will take. In the early phases, the maintenance cost to dismantle and assemble the components has to be estimated. Tolerance requirements and the time to assemble/dismantle each bolt around the flange will contribute to the total maintenance cost.

4 The Knowledge Enabled Engineering Approach

This section described the Knowledge Enabled Engineering (KEE) approach and how it was used to develop a multidisciplinary tool for flange design. KEE include KBE and other knowledge rich strategies, [15] and aim to solve the need with techniques or methods that fulfills the need. The purpose of KEE is to allow automation of engineering work as this creates an opportunity to extract knowledge normally found in later phases and make this knowledge available already in the conceptual phase. KEE is here described with three components: capturing of engineering knowledge, automation of engineering activities and quality control of engineering activities. KEE and KBE are similar in the way they are used for automating engineering activities. The difference is that KBE is often used in commercial KBE systems providing demand driven, object oriented programming languages.

4.1 Capturing of Engineering Knowledge

Engineering design comprises knowledge from many disciplines such as design, manufacturing and maintenance. As seen in section 2, approaches like ES, DR, KBE and CBR has been used to support engineering activities. The KEE approach aims to use the best-suited technique for each knowledge asset as it is believed that one technique cannot capture all engineering aspects.

The multidisciplinary flange design process contains knowledge from performance, manufacturing and maintenance activities. Knowledge was acquired through company reports and semi-structured interviews [16] with people involved in the flange design process holding design, manufacturing and maintenance positions. Below are examples of acquired knowledge from the design, manufacturing and maintenance disciplines.

One step in the design discipline is to evaluate the performance of the flange. Equation 1 is used to calculate the maximum force before bolt separation. This is done with the following equations:

$$\text{Max\_F\_Sep} = \frac{\text{Pre\_F\_L - Min\_Res\_Pre\_F - Res\_Pre\_F\_Comp}}{1 - \dfrac{\text{Bolt Stiffness}}{\text{Bolt Stiffness + Flange Stiffness}}} \tag{1}$$

$\text{Max\_F\_Sep} = \text{Maximum bolt force before separation}$

$\text{Pre\_F\_L} = \text{Prestressing Force Lower}$

$\text{Min\_Res\_Pre\_F} = \text{Minimum Residual Prestressing Force}$

$\text{Res\_Pre\_F\_Comp} = \text{Residual Presstressing Force due to Composing}$

In the manufacturing discipline the interest is to calculate the total time of the manufacturing process. Equation 2 calculates the cutting time for the turning operation and equation 3 calculates the drilling time.

$$\text{Cutting time} = \frac{\text{Area}}{\text{Fedd per revolution} \times \text{Cutting speed}} \tag{2}$$

$$\text{Drilling time} = \text{number of holes} * (\text{time to next hole} + \text{drilling time}) \tag{3}$$

One important function of the flange is to allow assemble and dismantle of jet engine components. The time to assemble the bolted flange joint is calculated in equation 4.

$$\text{Total Bolt Assemble Time} = \text{Number of Bolts} \times \text{Single Bolt Assemble Time} \tag{4}$$

4.2 Automation of Engineering Activities

This part is usually iterated with the capturing of engineering knowledge. Automation is a vital part of the KEE approach as automation allows fast iteration of engineering activities. Ideas can then be tested allowing engineers to simulate and design the product life cycle properties.

A company specific standard is used in the formalization process where the acquired knowledge is transformed into a reusable format understandable by a computer. The standard was structured in table form with columns named:

- **Service description** – describes the name of the class
- **Parent –** addresses the parent class
- **Property –** names of the rules in the class
- **Source –** specifies if the rule gets direct user input
- **Rules –** all the rules is outlined and their interactions between each other can be followed

The structure has been outlined to help the user to understand how the design tool is built up. All captured activities of the flange design process are captured into separate classes. More complex activities can have sub classes of sub activities. Property “Max_F_Sep” described in equation 1 is now represented by the parameter ‘Max_F_Sep’ defined inside the ‘Bolt Analysis CLASS’. The value of the parameter ‘Max_F_Sep’ will be automatically calculated if asked for in the ‘Bolt Analysis CLASS’.

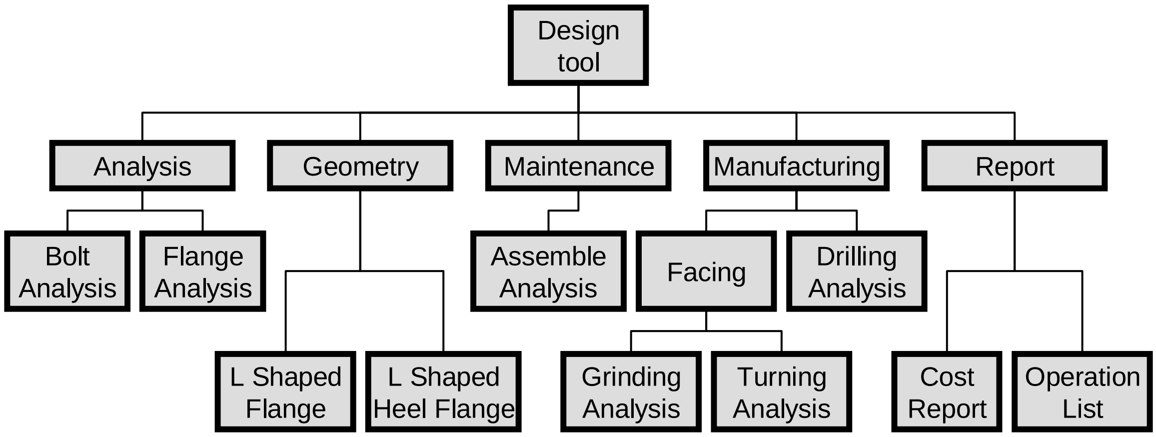

Figure 2. The structure of the multidisciplinary design tool.

4.3 Quality control of Engineering Activities

If a process is captured in a computerized system, it can be exactly repeated each time. Using the same procedure concepts can then be generated and evaluated. This quality assurance gives the engineers a reliable basis to compare concepts from. A captured process is now an asset of the company and can be reused whenever needed.

5 The multidisciplinary design tool

This section presents the multidisciplinary design tool. First, an overview is given of the main characteristics and the software components of the tool. Then, the connections between the disciplines are presented. Finally, it is presented how the tool can be used to work with parallel activities in product development teams.

5.1 Overview

A design tool suitable for multidisciplinary concept definition and evaluation is presented. The tool embeds processes from design, manufacturing and maintenance enabling the engineering designer to simulate parts of the product life cycle in the concept phase.

Figure 2 shows an overview of the design tool. The downstream process is performed and controlled through a GUI. First the user automatically generates a candidate product definition in a CAD program then the product definition is subject to evaluation in terms of performance, maintenance and manufacturing. One criterion in aero engine flange design is to prevent leakage that is evaluated in the performance step. The cost of component disassembly and re-assembly in the maintenance step and manufacturability in terms of drilling and facing can be evaluated. When an evaluation step is unsatisfactory a new product definition can be generated and this iteration continues until an appropriate product definition is generated. At this point all costs can be summarized in a cost report, which is governed, by a script and a database together with a spreadsheet. It should be noticed that all the decisions are still being made by humans with the support by the design tool ensuring a non redundant design.

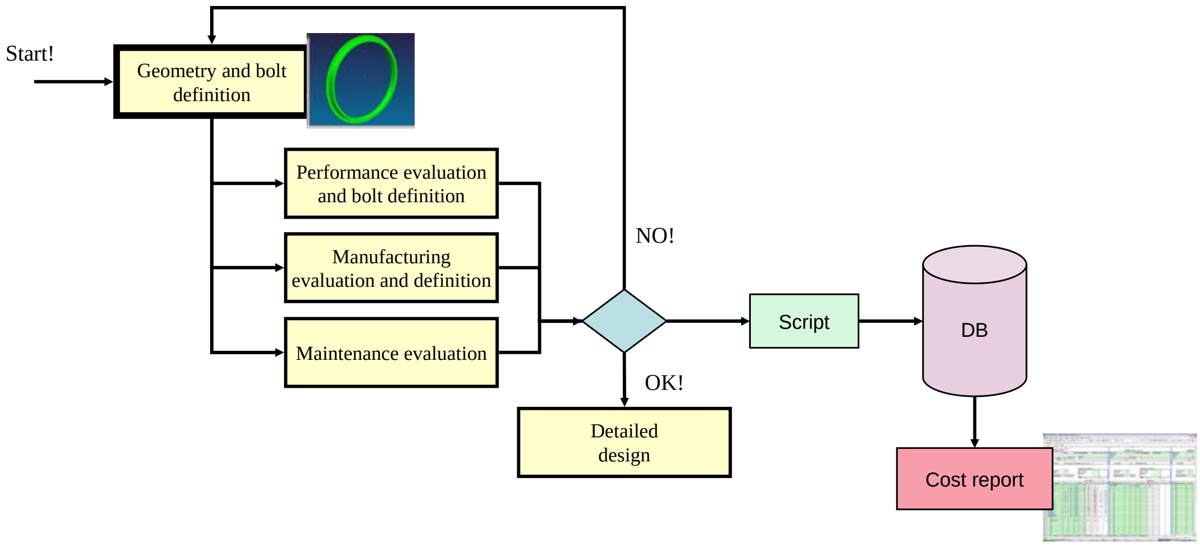

Figure 3. Design tool overview.

As all knowledge is implemented as rules connections between the activities are handled. This implies that one design variable change such as geometry (mantle width) affects many other variables in other activities such as flange mantle stress analysis. Figure 4 shows which activities that are affected when the geometry (red colored arrows) and bolts (purple colored arrows) are changed.

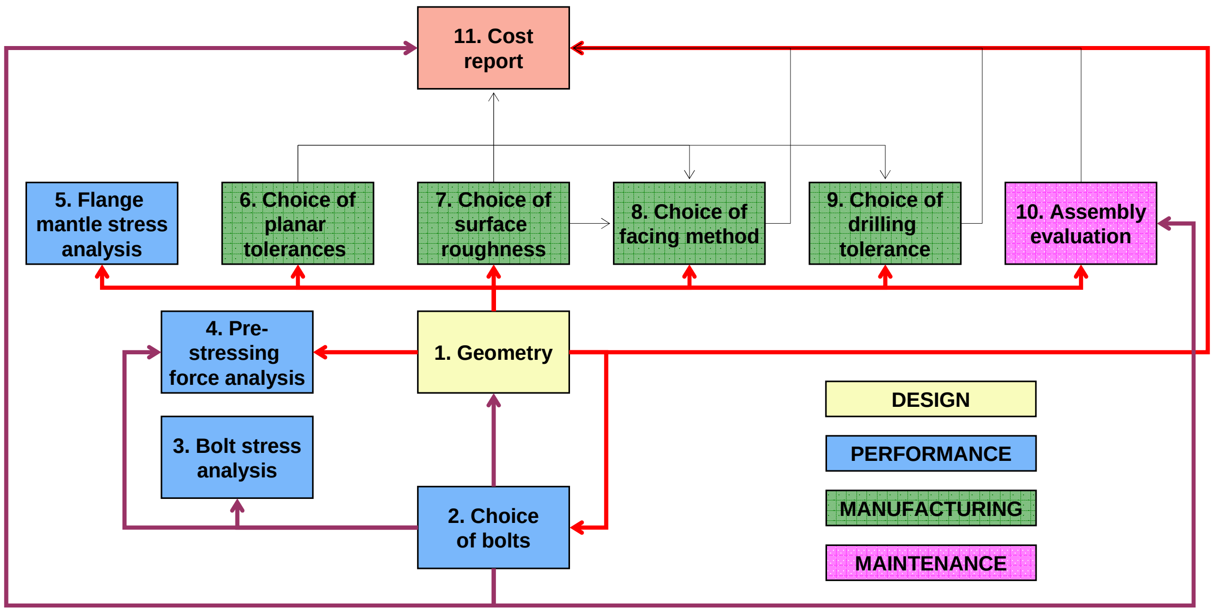

Figure 4. Activities affected when geometry (red colored arrows) and bolts (purple colored arrows) are changed.

The main interface (Figure 5) is used to specify initial dimensions, materials and manufacturing method. In the lower right corner there are three buttons that open “Analysis Properties”, “Manufacturing Properties” and Maintenance Properties” interfaces. From these interfaces the user is introduced to more parameters where the value either is typed in or chosen from a list.

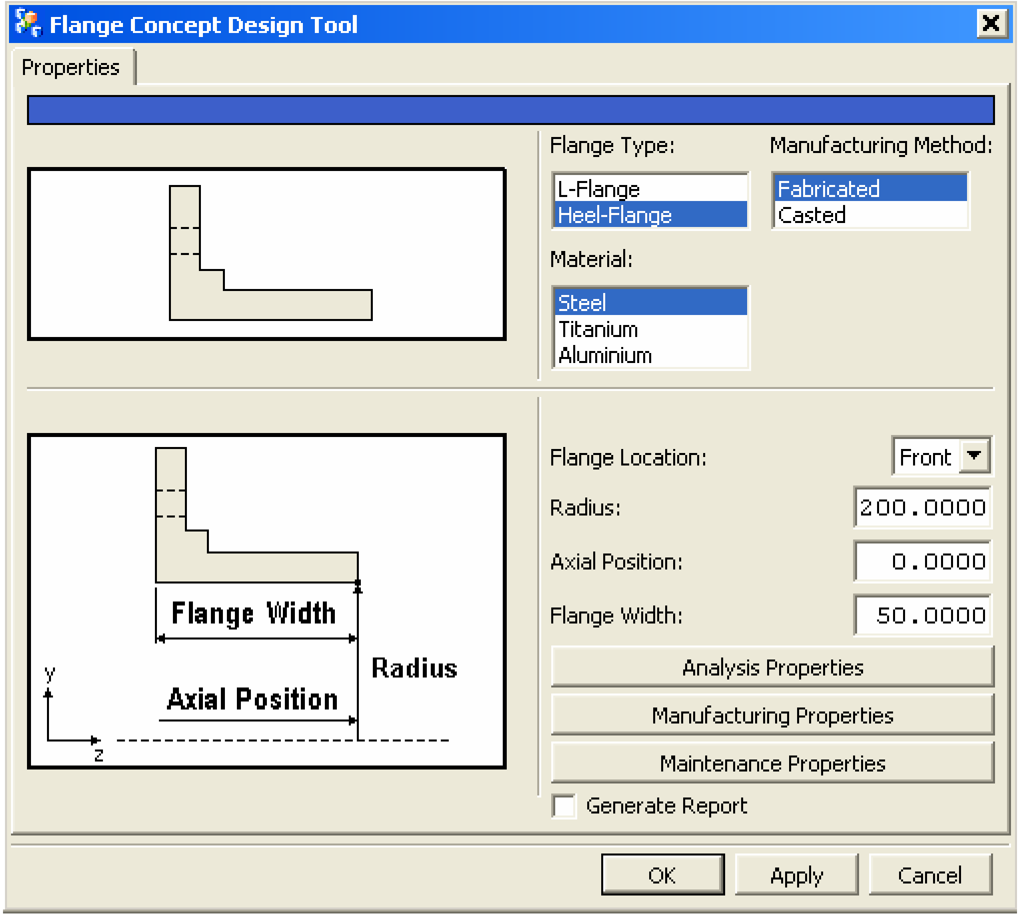

Figure 5. Main interface from where the user can specify dimensions, open analysis, manufacturing and maintenance interfaces and also toggle on report generation.

Design, manufacturing and maintenance engineers can with the help of the multidisciplinary design tool simulate how different decisions will affect each other. In figure 5 a comparison between how the cutting time is affected for constant surface roughness and change of material between steel, titanium and aluminum is shown. Another example where the choice of bolts affects both the drilling operation and the assemble time of the flange is shown in Figure 6.The immediate response given to the engineers creates an understanding between the engineers preventing design conflicts, especially in the early stage of product development where the requirements and constraints is usually imprecise and incomplete.

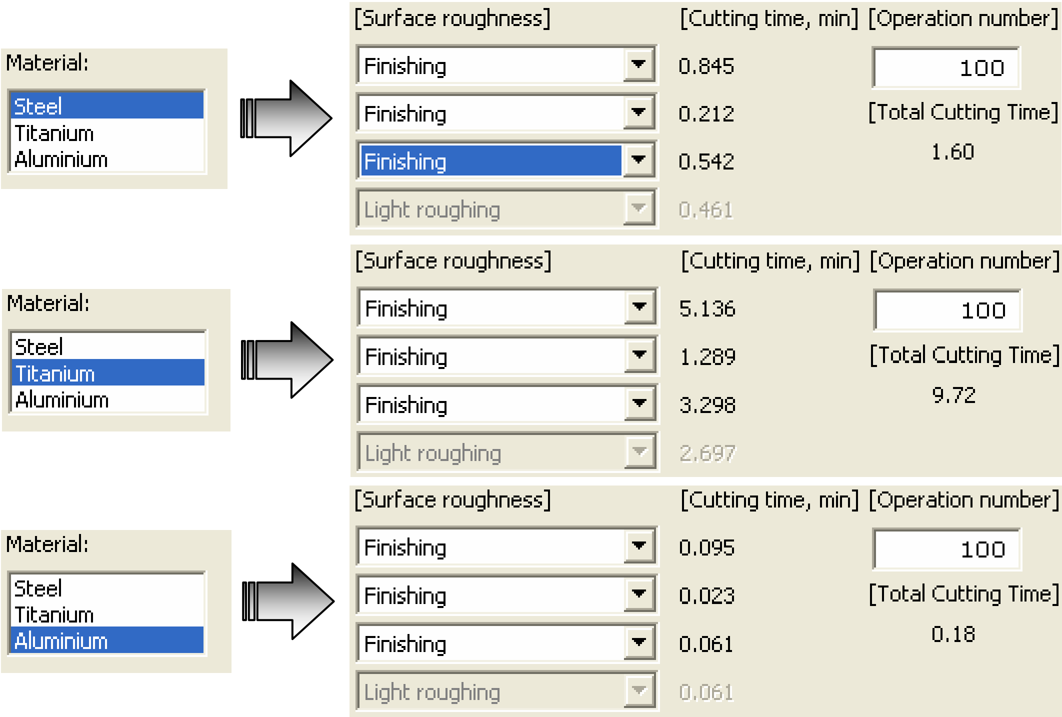

Figure 6. When choosing different material and surface roughness the user can directly see the effect on the total cutting time for the turning operation.

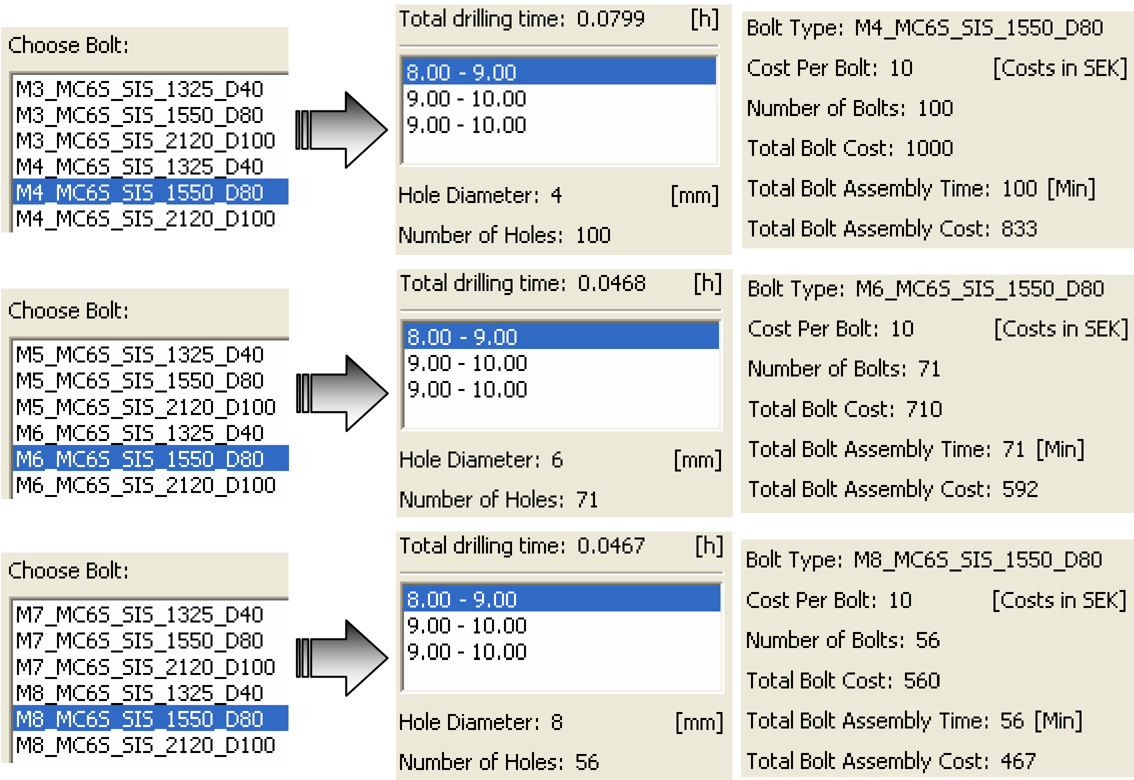

Figure 7. Choice of bolt affects the size of the hole and the number of holes which in turn affect the drilling and assemble time.

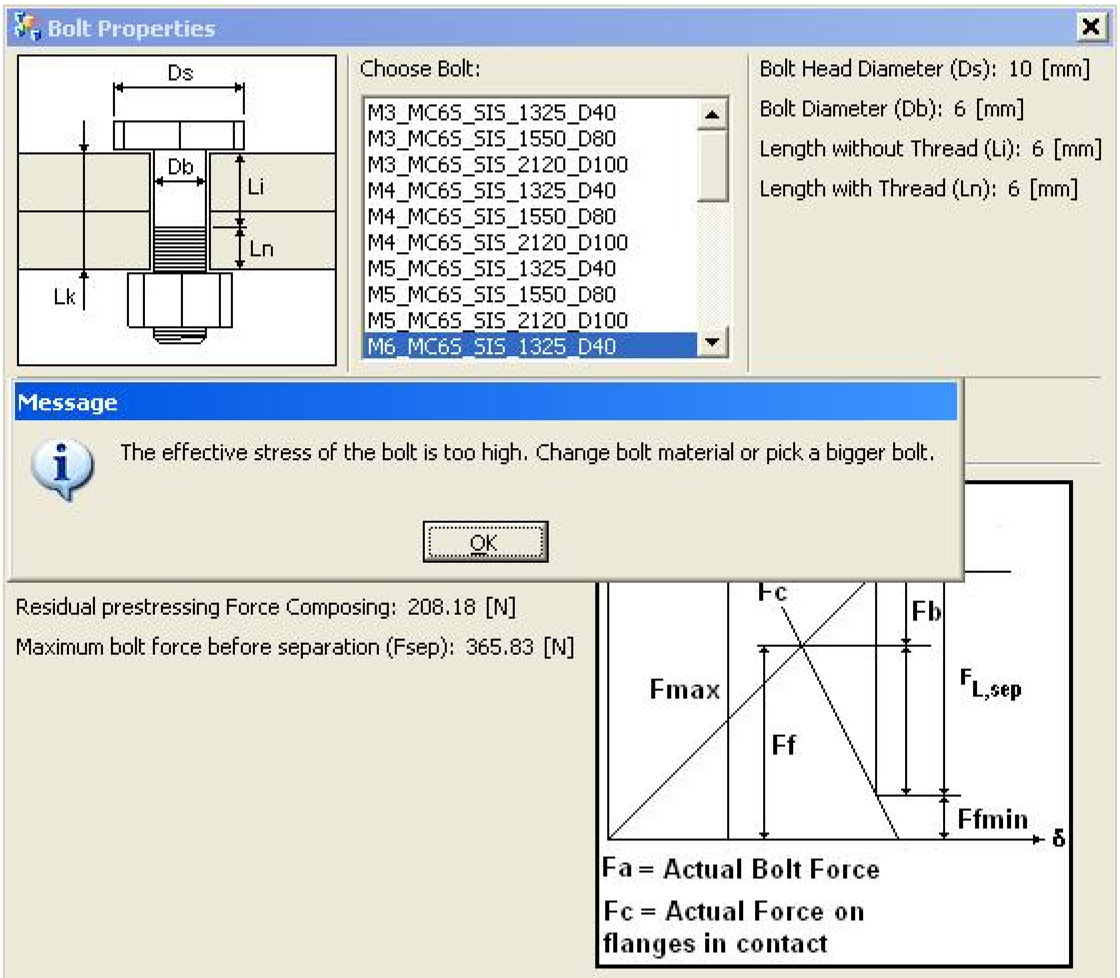

Figure 8. In this picture the result from equation 1 is found in lower left interface parameter. The figure also shows a warning message due to too high effective stress.

5.2 Supporting parallel engineering design activities

Using the tool it is possible to prevent design conflicts that can arise due to parallel processes. One possible conflict scenario could be: One engineer chooses facing method (activity 8) and wants to choose a rougher surface in order to make facing possible, because no facing method exists for the current chosen surface roughness. Another engineer chooses drilling tolerance (activity 9) and wants to make the surface less rough in order to allow precision drilling. The current solution is to choose the finest surface roughness which facing method exists for.

Regarding the conflict scenario described above the engineers can together use the tool and vary surface roughness and find the finest surface roughness for which a facing method exists for as this is implemented as rules. The drilling operation has to be planned according to this surface roughness. Pop-up error messages are generated when the chosen surface roughness conflicts a manufacturing method, see Figure 9 for drilling and facing GUI:s.

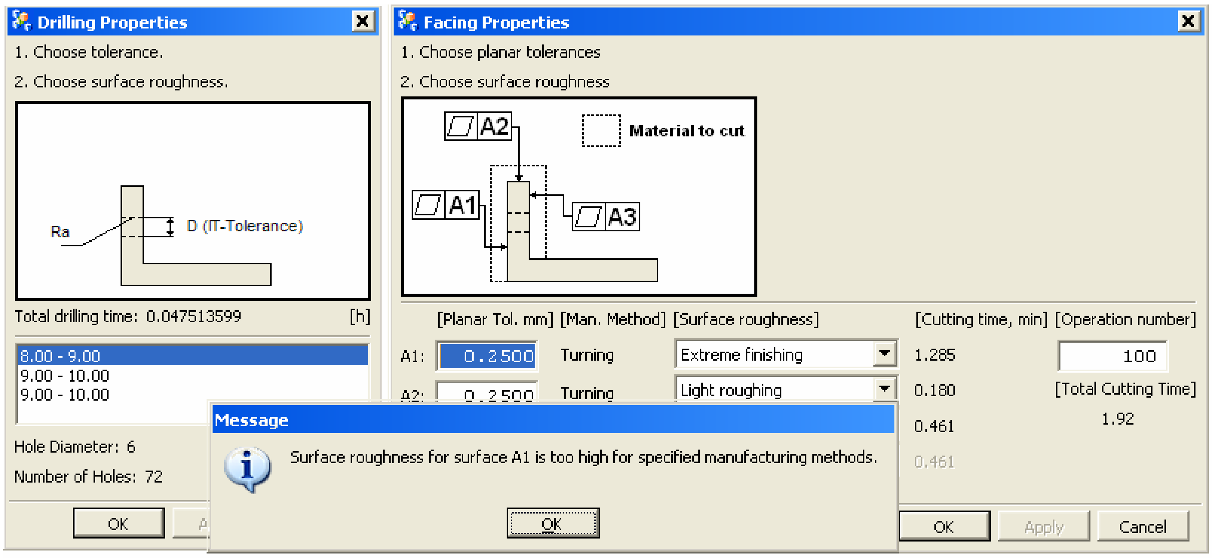

Figure 9. Preventing design conflict between drilling and facing functions.

6 Discussion

As conceptual and downstream product development knowledge is embedded in the multidisciplinary design tool it is possible to synthesis and directly analyze jet engine component flanges in terms of performance, manufacturability and maintainability providing the engineer a direct response of how much the chosen method, tolerance, etc., will affect the manufacturing and maintainability costs.

Using the tool, one design variable change triggers the change of many other variables which can be seen as an automation of some parts of the design process. This saves time and makes it possible to define and evaluate more concepts than without the tool. The design tool assures that the engineering activities are performed accordingly to company design specifications which create a better control over the process quality. The activities captured can now be performed whenever needed with a process that is validated. The tool can be used in design teams and can thereby prevent design conflicts that can arise due to otherwise parallel activities. Design, manufacturing and maintenance engineers can jointly use the tool and with their different expertise contribute to the flange design.

Design tools like the one presented in this paper creates new opportunities for exchange of knowledge between company disciplines. As engineers from different disciplines can discuss design requirements during meetings and simultaneously simulate life cycle properties a better knowledge base for design decisions is created. The increased understanding gives an overview enabling the engineers to better optimize the product life cycle properties and prevent sub optimization.

New opportunities are created with the described design tool giving the engineers a new way to simulate their concepts in real time. The new tool should be used on a global system level to optimize the total product system. This will be the next step in global product development not only between companies but also within large global companies to support their “cross-brand development”.

7 Conclusion

The design tool enables automatic generation of flange design concepts and it is possible to assess downstream aspects of performance, manufacturing and maintenance directly. Manufacturability in terms of operation cost for facing and drilling operations and maintenance cost can be assessed. As downstream activities are simulated in the design phase it is possible to see the impact in other disciplines and thereby correct design flaws that would cause downstream problems. The design tool assures that the engineering activities are performed accordingly to company design specification which creates a better control over the process quality. The tool creates a better understanding enabling the engineers to optimize the concept in real time from an overall product life cycle aspect. The new tool will be the base for optimization of the total product system and will be used not only between companies but also between product development departments in large global companies.

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