LICENTIATE THESIS

Knowledge enabled engineering design tools for manufacturability evaluation of jet engine components

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Preface

This research has been carried out at the Division of Computer Aided Design at Luleå University of Technology in collaboration with Volvo Aero Corporation (VAC), Trollhättan, Sweden. The research is funded by VINNOVA (Swedish Agency for Innovation Systems) through the programme *Tillverkningsindustrins produktframtagning*, by VAC and the Division of Computer Aided Design.

Doing PhD studies is a non-linear and iterative process, and I am thankful for the guidance I have received from many people. First, I would like to express my gratitude to my supervisors, Professor Lennart Karlsson and Assistant Professor Tobias Larsson, for initiating my research project, providing a unique research environment and for many enriching and interesting discussions. My co-supervisor, Tobias Larsson, has always been there with an ever-positive attitude: Tobias – thank you! At VAC, I would like to thank Patrik Boart for a good cooperation, and Dr. Ola Isaksson for valuable support.

Thanks, also, to my co-authors Henrik Nergård and Peter Åström for a fine collaboration. I would also like to acknowledge my colleagues at the division for contributing to a nice and stimulating working environment.

Finally, I wish to express my special gratitude to my wife Sara and my daughter Miriam for always being there for me.

Luleå, March 2005

Marcus Sandberg

Abstract

The success of manufacturing companies depends on their ability to produce high-quality products at the lowest cost. This applies to a jet engine industry that aims to create designs that are optimised for manufacture. In striving for lower cost, it may be worthwhile to focus on the concept phase of product development, since most of the product cost is committed there. This cost is, however, not often seen until it is allocated later or downstream in the product development process, for instance, during component manufacture. Currently, manufacturability assessment is often conducted manually in the jet engine industry, which takes time and entails the risk of missing design flaws. Life-cycle modelling has become a practical method of visualising this cost and enabling product analysis by simulating product development activities in design for manufacturing support tools. Support tools supplying manufacturability information during jet engine component design are, however, not common. The aim of this work is to discover how knowledge enabled engineering (KEE), an approach which includes engineering design, knowledge based engineering (KBE) and similar knowledge intensive methods, can be used to improve manufacturability evaluation of jet engine component concepts at a partner company.

KEE support tools supporting jet engine component flange design by including manufacturability evaluation have been developed in cooperation with a jet engine manufacturer operating in Sweden. The tools are based on a KBE module of commercial CAD software coupled to spreadsheets and a database. Flange designs can be evaluated in terms of facing and drilling operations. Manufacturability evaluation has also been extended by a connection through UNIX and Python scripts to a non-linear finite element analysis (FEA) program for automatic analysis of distortion due to mechanical cutting. Using the flange design tool, the designer can automatically generate concepts with different topological geometry features and directly assess mechanical cutting and drilling aspects. Operating costs, which are dependent on choice of planar tolerances and surface finish, can be estimated. With the tool extension, the designer can assess distortion with only basic knowledge of FEA. This can give the computational engineer additional time to concentrate on more intricate manufacturing simulations. The tools presented show how downstream manufacturing activities can be modelled using KEE, thus increasing possibility for evaluation, as best practice has been captured in a product model. This may improve product quality as poor manufacturability concepts can be avoided already in the concept phase.

Keywords: *Knowledge enabled engineering, support tools, engineering design, design for manufacturing, jet engine components*

Thesis

This thesis comprises an introduction and the following appended papers:

Paper A
Boart, P., Nergård, H., Sandberg, M. and Larsson, T. *A multidisciplinary design tool with downstream processes embedded for conceptual design and evaluation*. Accepted for presentation at International Conference of Engineering Design, Melbourne, August 15-18 2005.

Paper B
Boart, P., Sandberg, M., Nergård, H., and Isaksson, O. *A knowledge enabled engineering approach for conceptual design of life cycle properties*. Submitted to Journal of Computing and Information Science in Engineering.

Paper C
Sandberg, M., Åström, P., Larsson, T. and Näström, M. *A design tool integrating CAD and virtual manufacturing for distortion assessment.* Accepted for presentation at International Conference of Engineering Design, Melbourne, August 15-18 2005.

Contents

APPENDED PAPERS

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1 Introduction

This section first presents a background of the product development issues that justify this research. The actual research gap that this research targets is then addressed as well as the aim of the research. Lastly, the funding and research partners of the research project are presented.

1.1 Background

The economic success of manufacturing firms depends on their ability to identify the needs of customers and to quickly create products that meet these needs and can be produced at low cost, [1]. This is applicable for jet engine manufacturers aiming at optimising design activities for manufacturing. Visions [2] for the future of European aeronautics, in a 15-year timeframe, articulate among other goals:

- A 50% cut in CO_2 emissions per passenger kilometer (which means a 50% cut in fuel consumption in the new aircraft of 2020) and an 80% cut in nitrogen oxide emissions.
- Halve the time to market for new products with the help of advanced electronic analytical, design, manufacturing and maintenance tools, methods and processes.

Objectives like these present new requirements for the manufacturing firms, such as higher organizational flexibility, effectiveness and efficiency. Concurrent engineering (CE) [3, 4], defines the framework for how to integrate product and process organizations in order to achieve integrated product development and cope with requirements of this kind. Then, it is up to others to define the details of CE in terms of applications.

When an objective is to cut lead times, reduce costs and increase quality, a focus on the concept phase can be valuable, as a majority of the product cost is committed in the concept phase of engineering design [5]. This cost is, however, often not seen until it is allocated later, or downstream, in the product development (PD) process, e.g., during manufacturing. Therefore, there is a risk that engineering designers commit more manufacturing cost than needed. Manufacturability evaluation is currently often performed manually by teams of designers and manufacturing engineers [6]. Even though design flaws that result in poor manufacturability might be found manually before the actual manufacturing operation begins, it is plausible that time could be saved if the design flaw was found during conceptual design. This extra time for redesign need to be reduced as a part in halving the time to market. To cope with this, the manufacturing firm must employ methods and tools that enhance the engineering design process.

1.2 Research gap

Life-cycle modelling has become a popular way of supporting engineering design functions by simulating design and manufacturing activities [7]. Tools defined by methods such as case-based reasoning, expert systems and knowledge based engineering are quite common for product analysis and are more or less integrated into the product synthesis activity [8-10]. Support tools giving the designer a feedback of manufacturability during jet engine components design are, however, not common.

1.3 Aim

The aim of this work is to discover how knowledge enabled engineering, an approach that uses engineering design, knowledge based engineering and similar knowledge intensive methods, can be used to increase manufacturability evaluation of jet engine component concepts.

1.4 Research Project

A research project entitled *Design for fabrication* has been initiated to realize this aim. The project is a collaboration between Volvo Aero Corporation (VAC) and Saab Automobile both operating in Trollhättan, Sweden. During the work presented in this thesis, VAC has been the main partner. Project funding is provided by VINNOVA (Swedish Agency for Innovation Systems), as a part of *Tillverkningsindustrins produktframtagning,* by the partner companies and the Division for Computer Aided Design.

2 Knowledge areas

Product development is the overall process of finding customer needs and transforming those into a product for the market [1, 11]. Engineering design is a knowledge area that includes methods for how to carry out design with an engineering content, such as mechanical engineering design [12]. A branch of engineering design is design for manufacturing aiming at defining methods for making designs that are optimised for manufacturing [6]. Product life-cycle modelling is a means of making support systems, for instance, design for manufacturing activities [7]. Virtual manufacturing is a means of employing finite element analysis to assess manufacturability.

2.1 Product development

Ulrich and Eppinger [1] define product development (PD) as:

The set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product.

Isaksson [11] defines PD as:

Product development is the company process which takes the business requirements as a start and transforms these into a product.

Therefore, PD is multidisciplinary in nature, comprising, for example, engineering, economics and marketing. Product development is company-specific; but still, generic aspects can be found, which leads to methods. An overview of a generic PD process according to Wright [13] is shown in Figure 1. Although Figure 1 shows a sequence of activities, most manufacturing companies aim at integrating these activities so that they may be performed concurrently. A holistic method for such integration of all product development functions is provided Andreassen and Hein [14]. Prasad also presents method for how to achieve integrated product development through the integration of product and process organisations [3, 4]. The methods for product development give an overview of the organic, company-specific and ever-changing process. Less holistic, but still as important for the manufacturing firm, are the methods for engineering design, as they concentrate on PD activities with engineering content.

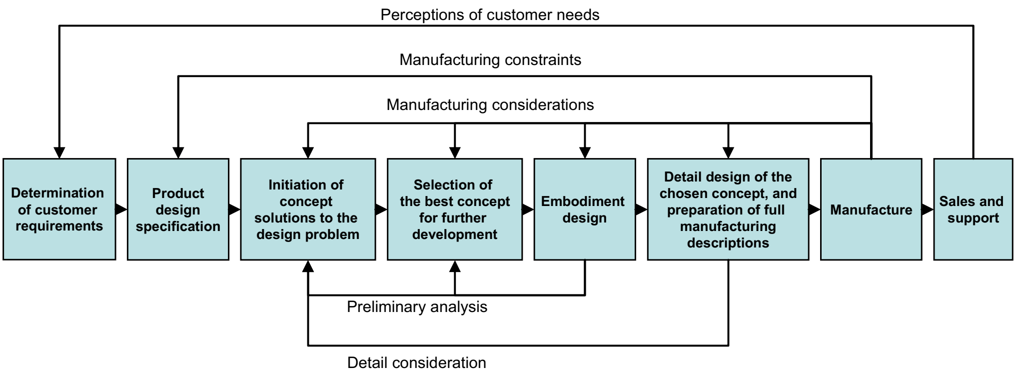

Figure 1. A product development process according to [13]

2.2 Engineering design

Dym [12] defines engineering design (ED) as:

Engineering design is the systematic, intelligent generation and evaluation of specifications for artefacts whose form and function achieve stated objectives and satisfy specified constraints.

Isaksson [11] defines ED as:

Engineering design is the general process of transforming design requirements into verified solutions.

ED methods in mechanical engineering have been presented by a number of authors [1, 13, 15]. As Andreassen and Hein [14] provide methods for how to integrate the activities of the PD process, Prasad [3, 4] also zooms in on ED and presents methods for how to make concurrent engineering possible. Several authors state that most of the product cost is committed in the initial part of ED, conceptual design [5, 16].

According to Ulrich and Eppinger [1], the following activities are included during conceptual design:

- identifying customer needs
- establishing target specification
- concept generation
- concept selection
- concept testing
- setting final specification
- project planning
- economic analysis
- benchmarking of competitive products
- modelling and prototyping.

These activities are generally iterated and often performed concurrently. This thesis is focused on conceptual design in terms of *concept generation, selection and testing* and *economic analysis* by means of *modelling and prototyping* in a CAD environment. In this thesis, CAD includes all computer tools that are intended for design of mechanical components.

2.3 Design for manufacturing

Design for manufacturing (DFM) is a specialised part of ED focusing on how to design manufacturable components. Goals are to minimise manufacturing cost and reduce number of product components. According to Boothroyd and Dewhurst [6], aspects that are in focus during design are:

- Early manufacturing visualisation and accurate cost estimating
- Supplier negotiation and communication tool
- Process and material selection
- Training and exposure for the engineers to the plants that manufacture the product they are responsible for
- 'Optimisation' of the manufacturability of all parts in the product, in order to ensure, improve and ease manufacturing.

If the above statements are taken into consideration, the best combination of materials, geometry and manufacturing method may be selected.

2.4 Product life-cycle modelling

Product life-cycle (PLC) modelling aims at simulating parts of a PLC by means of a model [7]. There are several approaches to PLC modelling, of which cased-based reasoning, expert systems and knowledge based engineering are discussed in terms of recent work. Cost is a common aspect to model in a PLC model. Cost can be modelled in numerous ways, which also are presented.

2.4.1 Case-based reasoning

Cased-based reasoning (CBR) is a technique that takes the design requirements and finds a recent design case that gives the best match. Marefat and Britanik [8] presents a tool that utilises CBR to plan manufacturing activities for a general prismatic part built up of slots, pockets and holes. Lou et al. [17] present a tool for mould-base design that is based on CBR and artificial intelligence (AI) techniques.

Marefat and Britanik [8] claims that CBR has many benefits in comparison with rule-based systems, which are often based on knowledge based engineering or sometimes expert systems techniques. Marefat and Britanik states that CBR is more efficient than rule-based systems, since the engineer does not have to start from scratch when generating the solution. Another drawback of rule-based systems is that it is difficult to maintain and ensure the consistency of the rule base as it gets larger. Finally, Marefat and Britanik claims that domain experts tend to explain their experience in terms of scenarios (cases) rather the rules. Although CBR has benefits, the number of solutions is dependent on the number of cases. Another issue is that when AI is included in a CBR system, as in [17], the quality of the result, i.e., how good the PLC is simulated, may vary from time to time, as the logics often are dependent on algorithms. This sort of logic, sometimes denoted fuzzy logic [18], and can be used to simulate PD activities that change often.

2.4.2 Expert systems

Expert systems (ES) are characterised as containing expert knowledge and are often used for analytic activities such as manufacturing evaluation. Venkatachalam [9] presents an ES for manufacturing evaluation in terms of drilling and milling.

As ES are often focused on analysis, automatic geometry generation is often omitted. Instead, it is quite common that ES are coupled to a geometry engine by which geometry definition is performed manually. Since, by definition, expert systems contain expert knowledge, they may become something of a black box, as some users may have difficulty understanding the expert knowledge these systems contain. As for CBR, ES often contain fuzzy logic techniques, which can be both a risk and a benefit, see also section 2.4.1.

2.4.3 Knowledge based engineering

Knowledge based engineering (KBE) is a method for building product models containing experience of engineering design and evaluation in terms of rules coupled to geometric parameters. Stokes [19] defines KBE as:

"The use of advanced software techniques to capture and re-use product and process knowledge in an integrated way."

KBE product models are often built up of objects in an object-oriented programming (OOP) hierarchy of classes and instances [20]. When one object changes in OOP, demand-driven capabilities calculate only the dependent objects instead of all parameters, as for procedural programming. KBE is suitable for products where the engineering content is more important than the industrial design content, as the objective is to capture engineering knowledge regarding repetitive and mundane activities. The smaller the difference is between product variants the greater is the reuse of engineering design experience by means of KBE systems.

Chapman presents a tool for evaluation of the car structural body in which mesh creation is automated [10]. The Parametric Composite Knowledge System (PACKS) is a tool for composite design that comprises embedded generic manufacturing processes for aerospace structure design [21].

Although both CBR and ES can be coupled to a geometry engine, it is more of a rule that KBE is coupled to a geometric engine. In contrast to ES, KBE focuses on routine, mundane and time-demanding knowledge instead of expert knowledge. KBE enables automatic creation of product definition in terms of geometry and manufacturing plans, for example. It is also possible to enable topological changes; a rectangular prism becomes a cylinder for instance, which is cumbersome if not impossible with traditional parametric solid modelling. Therefore, KBE includes both product synthesis and analysis. KBE systems can generate an infinite number of solutions, as the product model is not dependent on a finite number of cases. As all knowledge is represented as rules in the model, the output will always follow the real process, given that the real process has not changed since it was modelled.

2.4.4 Cost modelling

There are several ways of estimating cost [7]: parametric, analogous and detailed. A parametric model is defined as a model using equations with measurable attributes that are based on cost historical cost and technical information. Building a parametric model may involve considerable effort, since every attribute relationship needs to be modelled, but when finished, cost estimates can be generated swiftly. Analogous cost models aim at identifying the similarity between the current product and recent cases. The success of these models relies a lot on the judgment required by the model user. This approach is, however, claimed to be suitable for the development of new products. A detailed cost model according to [7] gives the most accurate cost estimation but is the most time-consuming and expensive approach of the three mentioned. It is expensive, because this model incorporates labour time and rates material quantities and prices, which can be a vast amount of information to acquire.

2.5 Virtual manufacturing

According to [22], virtual manufacturing (VM) will provide PD with:

"a modelling and simulation environment so powerful that the fabrication/assembly of any product, including the associated manufacturing processes, can be simulated in the computer."

Åström [23] is more focused on using FEA in PD, defining VM both with a product response focus and a manufacturing operation improvement focus:

- *Product response focus* – The use of FEA aims to investigate the response of the structure due to a manufacturing operation affecting the structural or global behaviour of the product. An example can be studying the increase in torsional stiffness of a car body due to spot welding. (No distinction is made here as to how the welds are modelled.)
- *Manufacturing operation improvement focus* – The use of FEA aims to predict the effect of a manufacturing operation on a product or component in terms of stress, plastic strain, displacements, temperature, microstructure, etc., so as to improve or optimise the manufacturing process itself.

VM therefore fills an important part in realising DFM.

3 Problem formulation

This section formulates the research problem in one question. The research approach, i.e., which methods were used to advance the research topic, is also discussed.

3.1 Research question

A question has been formulated in order to define the scope of this research:

*How can manufacturability evaluation be **enhanced** in the concept phase of the product development process **by means of knowledge enabled engineering**?*

Considering *enhancement,* it is crucial to know the current status of engineering design support tools for the jet engine industry. As noted in section 1.1, manufacturability evaluation is usually conducted manually in the jet engine industry. Therefore, possible manufacturing evaluation enhancements could be:

- creating a computer environment
- making manufacturing problems due to design flaws visible in concept design

With the notion *"by means of knowledge enabled engineering"* the scope of the research is set, as KEE is intended to be used to reduce the research gap described in section 1.2. Without this scope, any approach could be used to close the gap.

3.2 Research approach

Blessing [24] has presented a framework for design research, see Figure 2. The research presented in this thesis has been partly based on this approach. The research approach has been inspired by this method, although only the three first steps have been followed. The last step, 'descriptive study', is suitable for future work.

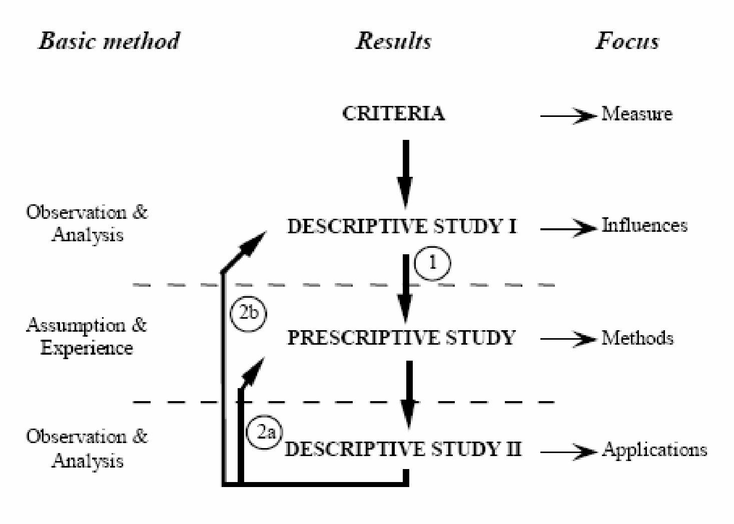

Figure 2. A framework for design research.

The first step, criteria, is to find a measurable criterion such as in this case, time to market or quality (number of poor manufacturability components per year, for instance), which can be used to assess benefit of the research result. The second step, descriptive study I, is to find the problems that have to be solved; i.e., how to improve manufacturability evaluation. The third step, prescriptive study, is to prescribe a way to solve the research problem; use KEE to increase manufacturability evaluation of jet engine component concepts. The last step, descriptive study II, is to measure whether the delivery from prescriptive study resolved the problem; engineering design tools.

4 Knowledge enabled engineering design tools for manufacturability evaluation of jet engine components

This section at first explains methods for KBE application development. Secondly, knowledge enabled engineering (KEE), an approach to support PD in terms of KEE applications, is described. Then, the partner company process chosen for case study is described. Lastly, the flange design tool and the tool integrating CAD and virtual manufacturing are presented.

4.1 Methods for KBE application development

Stokes et al. have recently presented the MOKA methodology for KBE application development [19] where, although a total application development cycle is outlined, knowledge acquisition and knowledge formalisation are in focus. This method is suitable for larger projects involving many people, since such project entail high regulation, special forms to fill in and require a special knowledge modelling language. Methods have, however, been proposed for projects in smaller organisations, [25]. Some claim that KBE application development does not dictate a particular approach, but that many follow a pattern similar to that which is used in normal design engineering problems [10]. The approach used by [10] is the following:

1. State problem
2. Identify required information
3. Create key product objects, *examples for an automotive structure could be: style, packaging, structural members, joints and panels*
4. Define initial conceptual product model, *blueprint of KBE application*.
5. Build subset of the overall system

The subset of the overall system can than be tested, used and extended with more accompanying subsets in an iterative process that is referred to as rapid application development.

4.2 Knowledge enabled engineering

Knowledge enabled engineering (KEE) is another approach that can be used to support product development by means of support methods and tools, i.e., KEE applications. KEE includes ED, KBE and similar knowledge-intensive methods [26], and the key concepts are defined as:

The key concepts are that the logics of the design object (artefact) and the actual design process are described in a way that allows generation of design solutions (i.e., geometries and more).

The chief difference between KEE and the approach described above, [10], is that KEE includes a wider set of knowledge techniques and an engineering design focus. The KEE application development strategy is therefore not restricted to a certain development method such as [19, 25]. Instead, the most suitable method is chosen; for instance, when developing a large business KBE application, MOKA is suitable. The application development strategy used in this thesis is quite similar to [10] and is described by presenting how it was applied for development of the tools in this thesis in terms of four steps: support tool need-finding, knowledge acquisition, knowledge formalisation and tool implementation.

4.2.1 Support tool need-finding

This activity aims to find the engineering design need for which a support tool can be developed, i.e., state the problem. This was done through meetings with involved people such as company staff and researchers.

4.2.2 Knowledge acquisition

Knowledge acquisition was performed at the partner company through formal and informal interviews and company reports. Managers and engineers with design, manufacturing, performance and maintenance functions were interviewed and are considered as representatives for the process.

4.2.3 Knowledge formalisation

The acquired knowledge was interpreted into rules and formalised to a computer-implementation-friendly format. Formalisation was done using a partner-company approach, see Figure 3.

Service Description	Parent	Property	Source	Rules
1.1.2 Bolt_Analysis_CLASS	1.1.1	1. Bolt Clearance 2. Hole Centre to Tip 3. Bolt Type 4. Lubricant … 16. Bolt load 17. Max. Bolt Force Separation …	1. Rule 2. Rule 3. User 4. User … 16.Rule 17.Rule …	1. Bolt_Clerance = 1.5 *Bolt_Head_Diameter 2. Hole_Dentre_to_Tip = 1.5 *Bolt_Head_Diameter 3. Bolt_Type = User Defined 4. Lubricant = User Defined … 16. Bolt_Load = Line_Load_at_Bolt / Number_of_Bolts * Pi * 2 *(Flange_Mantle_Middle_Radius + Middle_Mantle_to_Hole_Centre) * (Bolt_Stiffness / (Bolt_Stiffness + Flange_Stiffness))) 17. Max_Bolt_Force_Separation = (Prestressing_Force_Lower - Min_Residual_Prestressing_Force – Residual_Prestressing_Force_Composing) / (1 – Bolt_Stiffness/ (Bolt_Stiffness + Flange_Stiffness))
1.2.2 Turning_Manufacturing_CLASS	1.2.1	1. Material Add Factor 2. Material 3. Surface Roughness 4. Cutting Area 5. Feed per Revolution 6. Cutting Speed 7. Cutting Time	1. User 2. User 3. User 4. User 5. Rule 6. Rule 7. Rule	1. Material_Add_Factor = User Defined 2. Material = User Defined 3. Surface_Roughness = User Defined 4. Cutting_Area = User Defined 5. Feed_per_Revolution = f(Material, Surface_Roughness) 6. Cutting_Speed = f(Material,Surface_Roughness) 7. Cutting_Time = Cutting_Area/(Feed_per_Revolution*Cutting_Speed)

Figure 3. A partner company approach for knowledge formalisation.

During this activity the implementation structure, i.e., a hierarchical class structure, takes shape.

4.2.4 Tool implementation

When the acquired knowledge was formalised, implementation of the tool in a computer environment was started. Choice of software was adapted to the environment in which the tool should be used. To simplify tool introduction to a partner industry, using partner-industry software is preferable. The KBE module of Unigraphics Solution NX[1], Microsoft[2] Access database and Microsoft Excel were used for flange design tool implementation, see section 4.4. The finite element software MSC.[3] Mentat and Marc were used in the tool extension described in section 4.5 together with scripts defined in the languages provided by Python[4] and the UNIX operating system SunOS 5.8.

4.3 Current jet engine component design process

An idealised flange design process at Volvo Aero Corporation has been the case for design tool development. This section describes some characteristics of the flange design process.

4.3.1 Jet engine component flanges

Flanges occur on a number of jet engine components such as the low- and high-pressure case, intermediate case and exhaust case. The design of jet engine component

[1] http://www.ugs.com/products/nx/
[2] http://www.microsoft.com/
[3] http://www.mscsoftware.com/
[4] http://www.python.org/

flanges was chosen because it presented two major advantages. Firstly, the design has few features, allowing it to be modelled relatively quickly. Secondly, flanges are similar between jet engine component variants, which motivate the use of KBE.

A sketch of a jet engine component flange with examples of design requirements is presented in Figure 4. Jet engine components are often to some extent rotational-symmetric, which is why the modelled flange is chosen to be so.

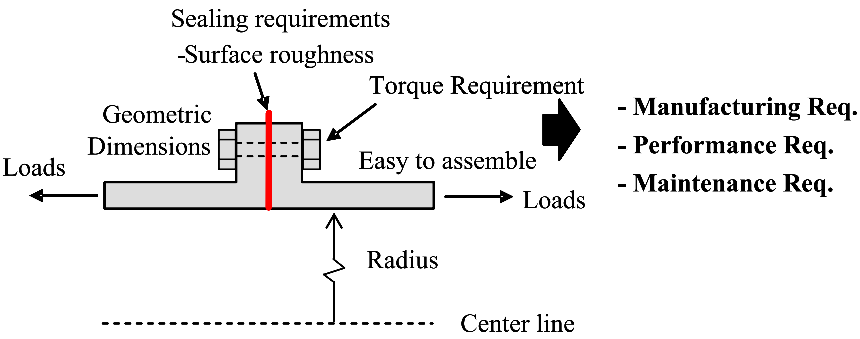

Figure 4. Two rotational-symmetric jet engine component flanges.

4.3.2 Manufacturability evaluation

When the required geometrical dimension and tolerances are set, a plan on how to produce the flange is created. A team of manufacturing engineers, weld engineers or other experts will define a suitable manufacturing process in terms of an operation list describing each manufacturing operation, including the manufacturing time.

4.4 Flange design tool

A flange design tool (FDT) has been developed through a case study of the design process described in section 4.3 at the partner company. This section gives an overview of the FDT and presents its manufacturing and cost aspects.

4.4.1 Overview

The FDT is build using a KBE module in commercial CAD software coupled to a database and a spreadsheet through a script. Rules concerning geometry definition, performance evaluation and bolt definition, maintenance evaluation and manufacturing evaluation and definition are implemented. An overview of the FDT information flow is presented in Figure 5. Graphical user interfaces (GUIs) govern the interaction between the user and the FDT. Firstly, candidate geometry is generated automatically and the user can vary dimensional parameters by changing input to the GUI. Then, performance, maintenance or manufacturing can be evaluated.

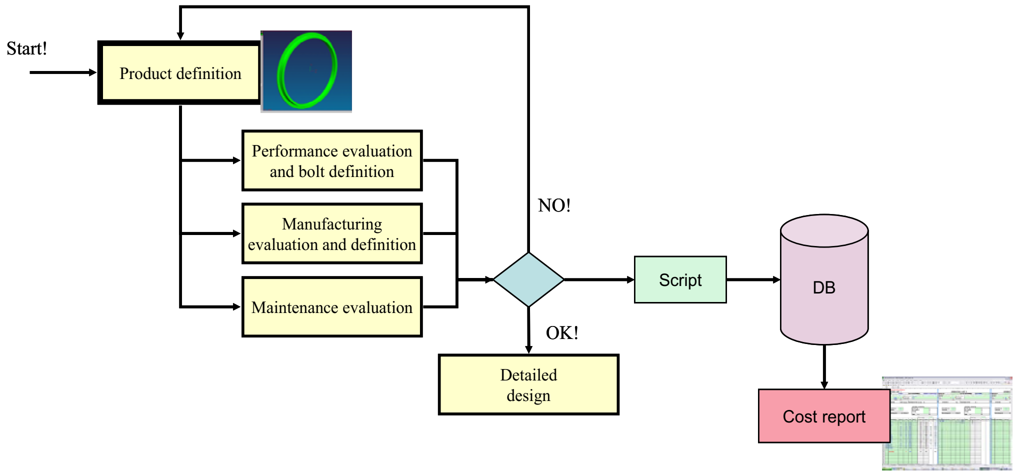

Figure 5. Flange design tool information flow

4.4.2 Manufacturing aspects

When a design has been generated, facing and drilling operations can be evaluated and defined. Using the GUIs, planar tolerance and surface roughness can be varied and the cutting time can be assessed, see Figure 6. If a planar tolerance or surface roughness conflicts with the manufacturing operation, an error message is generated, see Figure 6.

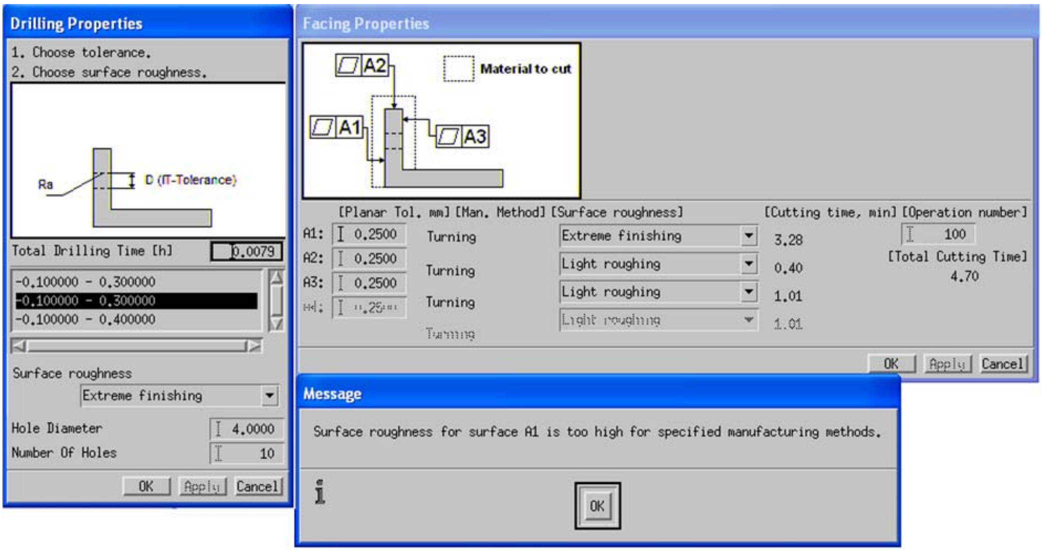

Figure 6. Manufacturing GUIs

4.4.3 Cost modelling

The cost model is parametric and based on the acquired knowledge, such as the expression seen in Eq. 1

$$\text{Cutting time} = \frac{\text{Area}}{\text{Feed per revolution} \times \text{Cutting speed}} \qquad \text{(Eq. 1)}$$

Where 'cutting time' is multiplied by the machine cost. This cost can together with drilling cost be automatically written to a company-specific manufacturing plan spreadsheet.

4.5 Tool integrating CAD and virtual manufacturing for distortion assessment

The FDT described in section 4.4 has been coupled to a non-linear finite element code by means of UNIX and Python scripts to enable a designer to assess distortion due to mechanical cutting whilst designing the flange. The automation of the FEA software is performed by macros that are managed by the scripts. An overview of the design tool can be seen in Figure 7. Firstly, the user defines initial flange geometry through the user interface. Secondly, number of cuts, cutting direction and cutting order can be set before the analysis is submitted to the FEA software. Scripts and FEA software macros define a mesh and boundary conditions from the given input, start the analysis and finally send the distortion results back to the user interface. The user can then decide if design and cutting changes are needed.

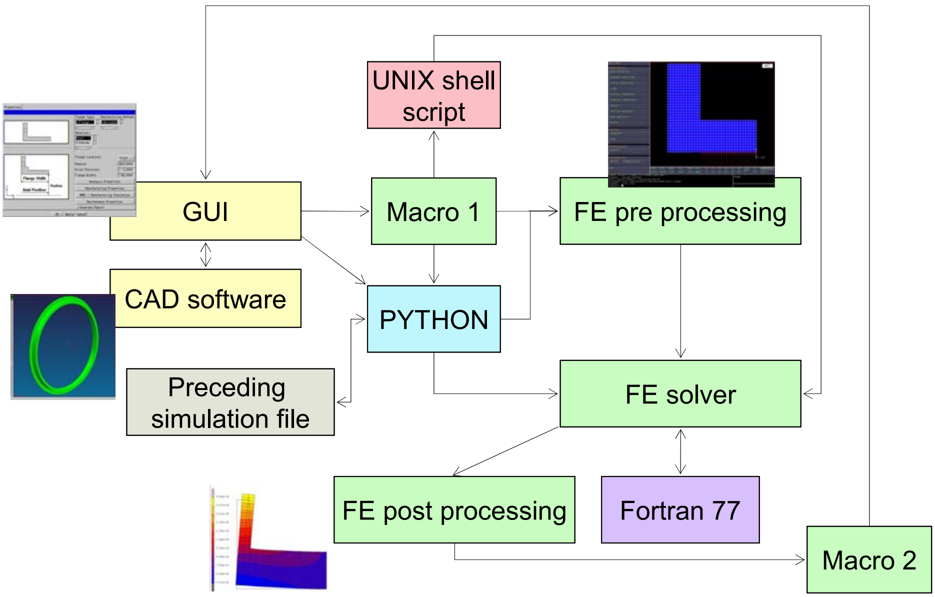

Figure 7. Overview of the design tool integrating CAD and virtual manufacturing

5 Summary of appended papers

This summarises the appended papers, their relation to the thesis and their individual results.

5.1 Paper A

Boart, P., Nergård, H., Sandberg, M. and Larsson, T. *A multidisciplinary design tool with downstream processes embedded for conceptual design and evaluation*. Accepted for presentation at International Conference of Engineering Design, Melbourne, August 15-18 2005.

5.1.1 Summary

Paper A shows how a multidisciplinary design tool can be used to embed knowledge from downstream design, manufacturing, maintenance and sales activities. The tool enables conceptual design and analysis of life-cycle properties of the hardware part of functional products. A knowledge enabled engineering approach is used to capture knowledge or best practice from the engineering activities needed to design and evaluate flanges. With the design tool, it is possible to simulate how life-cycle cost is affected by design decisions. The design tool feedback is direct, providing a direct response of how much chosen material, tolerances, etc., will affect the life-cycle cost. Instead of designing from a technical specification, the engineers can design with the business agreement in focus.

5.1.2 Relation in thesis

Paper A presents how the multidisciplinary design tool can be used to support engineering design activities when product development knowledge is actually embedded in the support tool.

5.1.3 Results

The embedded flange design knowledge enables quality control, as poor manufacturability can be avoided already in the concept phase. It shows how the user can make design changes and directly assess manufacturing operation cost and whether a tolerance or surface roughness can be met with the existing machinery.

5.2 Paper B

Boart, P., Sandberg, M., Nergård, H., and Isaksson, O. *A knowledge enabled engineering approach for conceptual design of life cycle properties*. Submitted to Journal of Computing and Information Science in Engineering.

5.2.1 Summary

The aim of paper B is to examine the possibility of implementing life-cycle properties in a commercial engineering design system. A flange design process is chosen as a case study. To support the process, a generative model is used to extract downstream knowledge from activities in different disciplines to objects and allow simulation of life-cycle properties. The model will be used for strategic decisions when developing total offers.

5.2.2 Relation in thesis

This paper targets the gap of design support tools for total offer development with a computer modelling focus presenting a flange design tool. Knowledge acquisition, knowledge formalisation and application structure are presented together with an example of tool usage.

5.2.3 Results

The paper demonstrates how objects can hold manufacturing knowledge and discusses how these objects can be adopted for use in generic products, as the objects can be inherited to other classes. Using KEE, all repetitive manufacturing evaluation knowledge can be captured, as the approach includes more methods than just KBE.

5.3 Paper C

Sandberg, M., Åström, P., Larsson, T. and Näström, M. *A design tool integrating CAD and virtual manufacturing for distortion assessment.* Accepted for presentation at International Conference of Engineering Design, Melbourne, August 15-18 2005.

5.3.1 Summary

Paper C presents a design tool which couples the simulation of distortion effects due to machining with CAD, where knowledge of how to perform a machining simulation is captured within the tool. The tool system is governed by a UNIX shell script and uses Python scripts for pre- and post-processing purposes coupled to the finite element software MSC.Marc™. The tool allows an engineer to estimate the distortion effects due to machining and is believed to help bridge the gap between design and computational engineers in the manufacturing planning stages of engineering design. By using tools like the one presented here, both component quality and accuracy of machining operation cost estimation can be expected to increase, since distortion problems can be solved or prevented already in the manufacturing planning stages of engineering design.

5.3.2 Relation in thesis

This paper presents an effort to develop a design support system to help in bridging the gap between engineering designers and computational engineers. It explains how the FDT presented in paper A and B was coupled to the finite element software MSC.Marc.Mentat™ and how distortion assessment of mechanical cutting was automated.

5.3.3 Results

Manufacturability can be enhanced further, as FEA adds detailed assessment capabilities. The user can change the design and then submit an analysis, which is performed automatically and finished within a few minutes time. Assessment of the distortion output from the analysis can then guide further design changes. Computational engineers can concentrate on more intricate tasks, while the designer can assess manufacturability in terms of routine FEA.

6 Discussion and Conclusion

This work aims at improving manufacturability evaluation in the conceptual phase of engineering design. Design tools for jet engine component flange design have been developed to exemplify this objective.

The contributions of this work are new methods for manufacturability evaluation in conceptual design. These contributions can be summarised as:

- *Providing a computational environment for facing and drilling evaluation.* This enables an easier design optimisation for facing and drilling operations, which increases product quality and reduces cost, as redesign can be minimised. It can also reduce time to market, as the evaluation process is automated. Since all acquired knowledge is formalised and implemented into a computer product model, quality control is enabled, as all output from the model follows the logics of the rules for every generated concept.
- *Describing how manufacturing knowledge captured in objects can be used for generic products.* This saves time when building new product models, as earlier data code can be reused. It also gives a framework for manufacturing implementation structuring, i.e., how to define the class hierarchy of the data code.
- *Presenting an outline for integrating design and virtual manufacturing in support tools.* This increases the ability for concurrent engineering, as engineering design activities can be integrated. It can also give the computational engineer more time for advanced FEA, while the designer can perform the routine FEA by using the tool.

7 Future work

Future work may include application of the methods for manufacturability evaluation on other products where a reuse of product development knowledge is possible, for example, on automobiles. Also of interest is the exploration of new methods for knowledge modelling such as CBR and compare the results with modelling experience from KBE work. Refining the cost modelling by incorporating more cost drivers such as machine availability, other manufacturing operations, for example, casting and welding, is also important to enable better prediction in the conceptual phase.

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Paper A

INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 05 MELBOURNE, AUGUST 15-18, 2005

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

Patrik Boart, Henrik Nergård, Marcus Sandberg and Tobias Larsson

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.

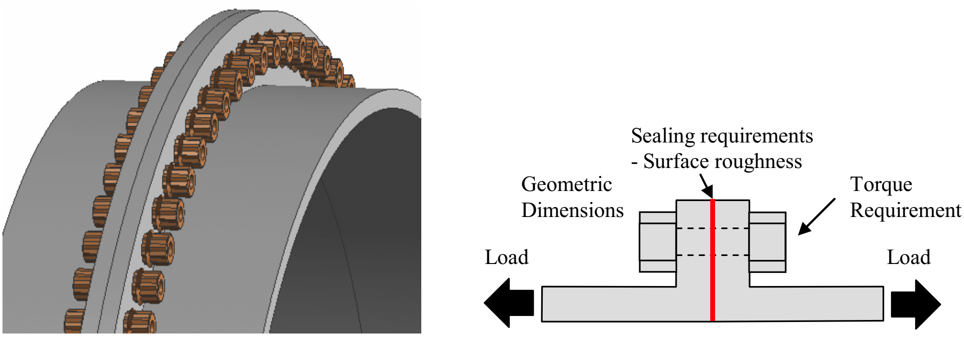

Figure 1. Section of a circular flange where the right picture displays the requirements and loads.

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:

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

Max_F_Sep = Maximum bolt force before separation

Pre_F_L = Prestressing Force Lower

Min_Res_Pre_F = Minimum Residual Prestressing Force

Res_Pre_F_Comp = 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.

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

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

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.

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

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’.

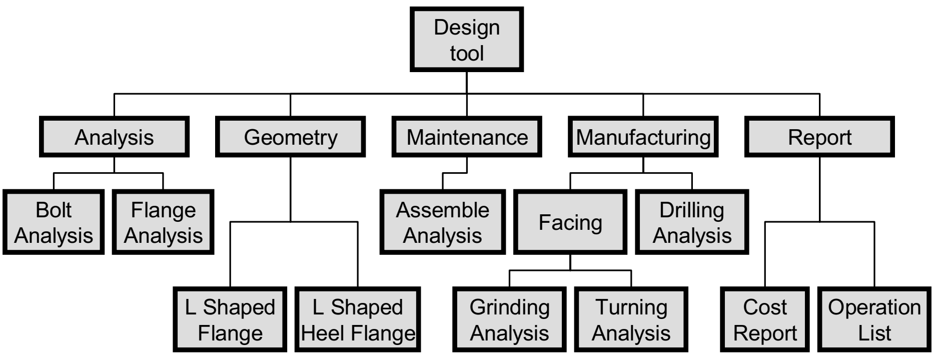

Figure 2. The structure of the multidisciplinary design tool.

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.

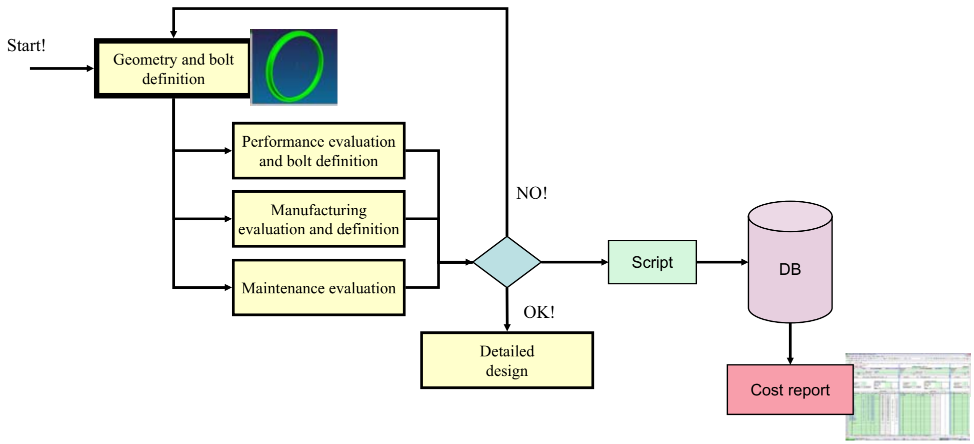

Figure 3. Design tool overview.

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.

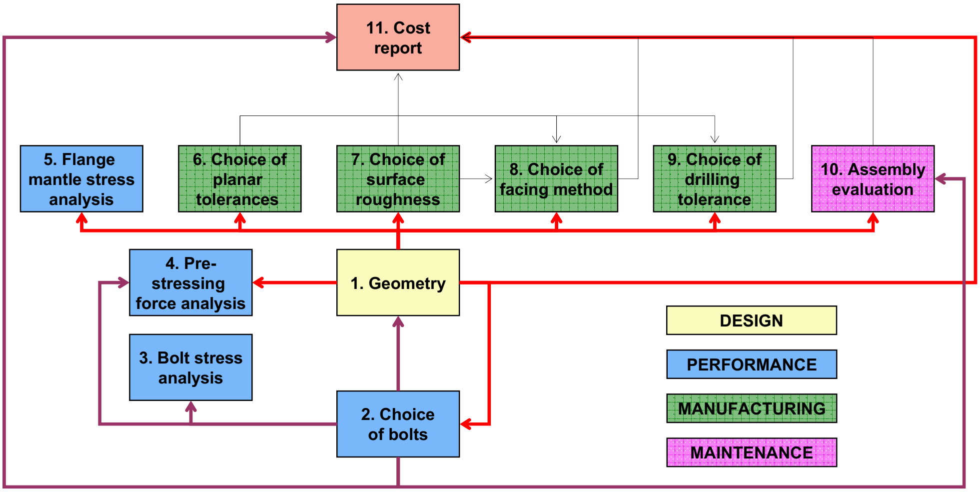

Figure 4. Activities affected when geometry (red colored arrows) and bolts (purple colored arrows) are changed.

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.

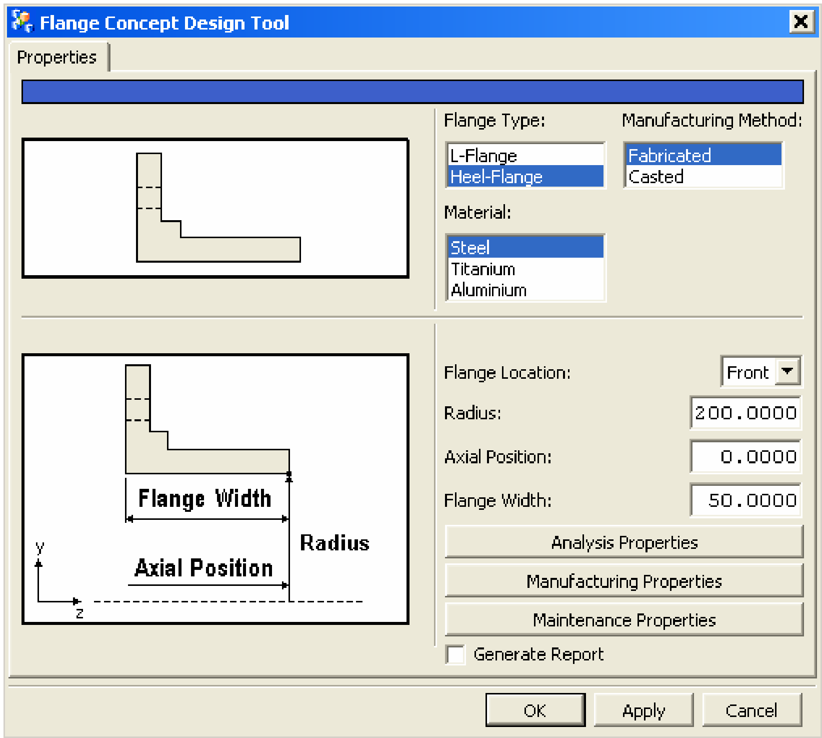

Figure 5. Main interface from where the user can specify dimensions, open analysis, manufacturing and maintenance interfaces and also toggle on report generation.

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.

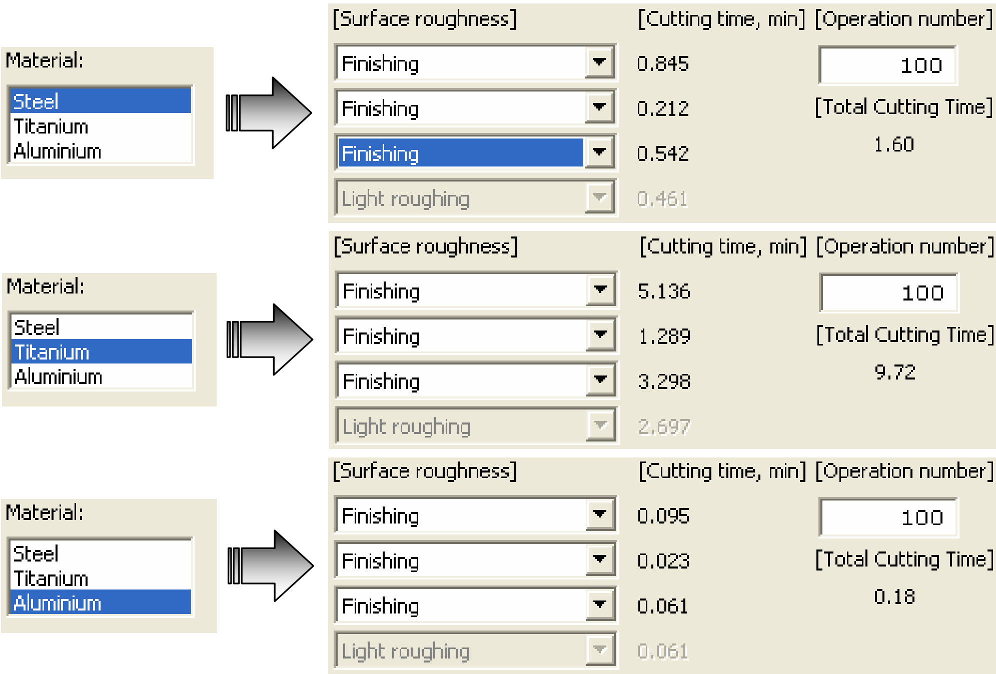

Figure 6. When choosing different material and surface roughness the user can directly see the effect on the total cutting time for the turning operation.

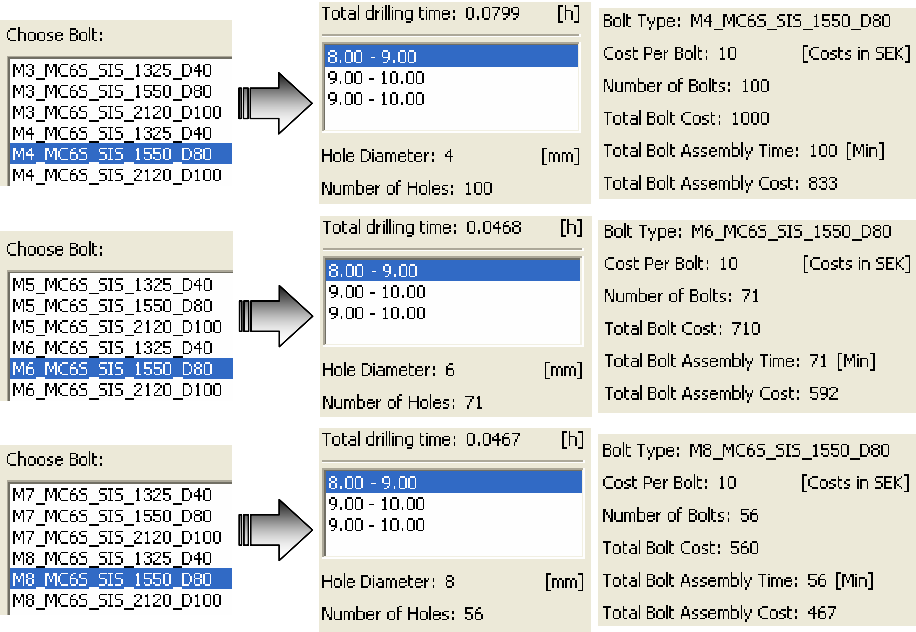

Figure 7. Choice of bolt affects the size of the hole and the number of holes which in turn affect the drilling and assemble time.

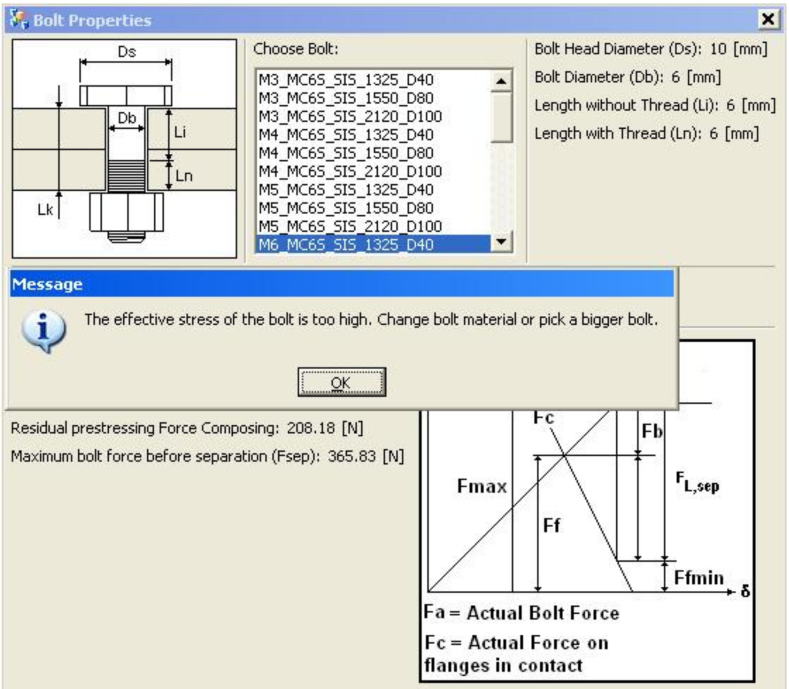

Figure 8. In this picture the result from equation 1 is found in lower left interface parameter. The figure also shows a warning message due to too high effective stress.

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.

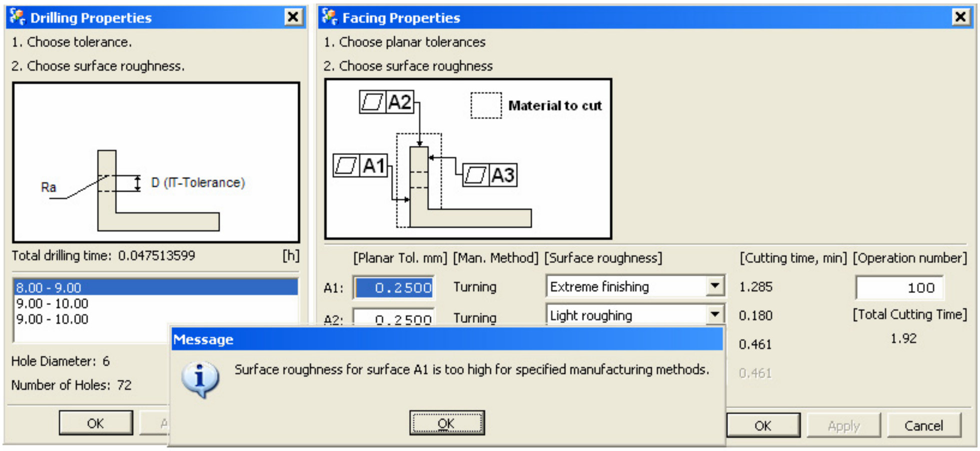

Figure 9. Preventing design conflict between drilling and facing functions.

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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Paper B

A knowledge enabled engineering approach for conceptual design of life cycle properties

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1 Abstract

Aerospace business agreements are being made on a life cycle basis where the actual product ownership often remains with the manufacturer. The aim of this paper is to examine the possibility to conceptualize life cycle properties in a commercial engineering design system. A flange design process is chosen as a case study. To support the process a generative model is used to extract downstream knowledge from activities in different disciplines and allow simulation of life cycle properties. The model will be used for strategic decisions when developing total offers.

Keywords: Knowledge Enabled Engineering, Aerospace, Manufacturability, Concept design, Engineering Design

2 Introduction

Business to business cooperation is undergoing large changes that closely fits the transformational driving forces, for example those identified by Swedish Technology Foresight on future product systems 2015 [1].

- *Individuals and companies act on local as well as global markets.*
- *Circular business systems: closed resource flows and scale of functions.*
- *Intellectual capital is the most important means of competition.*
- *Complexity in upcoming systems is leading to new demands.*

Business is changing due to the trends presented above, creating new requirements on how to develop products in business to business relations. This will force companies to optimize their part of the product system relating to the total product system. Aerospace business agreements are being made on a life cycle basis where the actual product ownership often remains with the manufacturer. The revenue for aero engine manufacturers and their engine programs appear late in the engine life cycle, not during market introduction where large discounts are common. An engine developed for the sale of spare parts is not optimized for the owner. The key when owning and producing engines is to develop engines with minimum life cycle cost.

Few support tools exist for the conceptual phase in engineering product development [2]. A company is therefore dependent on experienced personnel to make the right decisions. An aircraft engine is a rather complex product involving many disciplines during development. Conceptualizing products consisting of hardware, software and services during the life cycle is a rather demanding task with little time usually being spent during the conceptual phase. Improved system support is needed in the conceptual phase to handle the increase of information in future products. Limited knowledge about the product's life cycle exists in the conceptual phase, though important decisions affecting the cost of the life cycle are still made here. A need to simulate what effects the choices made have on the product life cycle has risen because aerospace business agreements are being made on life cycle basis. Capturing an activity from a product development process into a computerized support system allows it to be performed automatically. The knowledge within the captured activity can then be extracted and used where needed. It becomes possible with such a system to simulate events further down in the product's life cycle (downstream knowledge) in the early design phases where costs are committed, providing better control of the products life cycle cost and an increased accuracy when estimating eventual profit.

The aim of this paper is how to conceptualize life cycle properties in a commercial engineering design system for a company in a business to business environment selling a total offer [3] instead of hardware.

The study shows how design variables needed to evaluate the product life cycle effects can be captured in a commercial engineering design system. This is be demonstrated on a jet engine component flange with different performance and life cycle requirements. The article commences with a review of related work with tools created to support different activities within the area of engineering design, followed by an explanation of the Knowledge Enabled Engineering approach. A description of a flange design process is then given where design, manufacturing, maintenance and cost report knowledge are captured and formalized. From the formalized knowledge, the structure of the application can then be built and coded. A demonstration of the final Knowledge Enabled Engineering application is given at the end.

3 Related Work

Best practice in Engineering Design (ED) is continuously changing. Knowledge Based Systems and especially Knowledge Based Engineering (KBE) Systems are being used more frequently to store knowledge and support design processes [4-7]. Currently, product and process experience are often person dependent [2], where staff turnover causes loss of experience. Another issue is that products become more complex, with development requiring the involvement of more disciplines. These issues force companies to adapt their work practice to better account for multidisciplinary knowledge in the conceptual phase. Historically, KBE was developed by using principles from Expert Systems technology and CAD systems. Expert Systems coupled to CAD-tools emerged in the 1970s as a way of controlling and evaluating the geometry by means of rules [8]. KBE differed from Expert Systems by supporting tedious and repetitive work rather than expert knowledge reasoning [4]. Some claim that Expert Systems were unsuitable for Engineering Design situations and therefore failed [9]. Furthermore, KBE applications were designed to support both synthesis and analysis activities in the engineering design process.

Companies accumulate knowledge and experience during product development and through the operation of the product. A challenge is to maintain this knowledge and use it efficiently, while reducing the amount of routine work and release time to increase the space of creative solution exploration. However, how is this done in a company with established design systems? Engineers tend to spend a significant portion of their time creating various geometric models, and since this work is tedious and often rather repetitive in character, it should be a candidate for KBE modeling. The same types of models are often created over and over again containing a minimum of innovation and little re-use of pre-existing know-how [9]. Parametric CAD-models are a way of storing some amount of knowledge, enabling the solid model to be scaled and reused. However, it is difficult to make “traditional” parametric models that allow topological changes in the geometry. Likewise, it is not obvious how to associate non-geometric design variables to the parametric CAD model. Expert systems previously tried to solve these issues. A number of knowledge modeling techniques have been used to support different steps in the product development. An overview is used to show where and how they have been used, Table 1.

Knowledge Modeling Technique	Product	Discipline	Discipline relationship	Author
Expert system (ES)	Generic	Design, Manufacturing	Feature extraction and cost estimation of manufacturing	Venkatachalam [10], 1993
Design rationale (DR)	Kitchen design	Design	Capturing of design rationale for design of kitchen	Mørch [11], 1994
	Chemical Plant	Design	Capturing of design rationale behind a chemical plants	Chung and Goodwin [12], 1998
Knowledge based engineering (KBE)	Wing Structure	Performance and manufacturing	Performance and manufacturing analysis of a wing	Zweber et al. [13], 1998
	Wing Structure	Design, Cost analysis	Design, Cost estimation (manufacturing concerns)	Blair and Hartong [6], 2000
	Car body structure	Design, Analysis	Preprocessing of design	Chapman and Pinfold [7], 2001
	Aerospace	Design, Analysis, Manufacturing	Manufacturing and performance evaluation of design	Schueler and Hale [5], 2002
	Buildings	Design, Analysis	Cost estimation, scheduling on buildings	Mohamed and Celik [14], 2002
Agents and case based reasoning (CBR)	-	Manufacturing, Analysis	Molding evaluation	Lou et al. [15], 2004
	Insurance	Analysis	Risk analysis of drivers	Daengdej et al. [16], 1999
	Low Power Transformers	Design, Analysis	Product and process design	Kwong and Tam [17], 2002
	-	Design, Analysis	Material selection	Amen and Vomacka [18], 2001
	Travel Agency	Analysis	Travel planner	Chaudhury et al. [19], 2004
	Induction motors	Product Support	Diagnostics	Yang et al. [20], 2004

Table 1. Some Knowledge Modeling Techniques.

All the knowledge modeling techniques presented in Table 1 have different advantages depending on what knowledge is of interest to capture. Design Rationale, for example, captures decisions made during design so as to not lose the knowledge behind how and why certain decisions were made. A number of definitions on KBE system exist, see Table 2. Still, there are always parts in the process that the commercial KBE systems lack the ability to handle. This is where a new approach called Knowledge Enabled Engineering can be used, by incorporating KBE and other knowledge rich strategies [26]. This method will be based on existing theories and incorporate company engineering methods and systems.

Definitions on Knowledge Based Systems	Author
"Knowledge-Based Systems are a special class of computer programs that purport to perform, or assist humans in performing, specified intellectual tasks."	Dixon [21]
"KBE systems aim to capture product and process information in such a way as to allow businesses to model engineering design processes, and then use the model to automate all or part of the process."	Chapman [7]
"A Knowledge-Based System is the one that captures the expertise of individuals within a particular field, and incorporates it and makes it available within a computerized application. *A KBE application is further specialized and typically has the following components:* *Geometry* *Configuration and* *Engineering Knowledge."*	Lovett [22]
"KBE is a technology that allows an engineer to create a product model based on rules that capture the methodology used to design, configure and assemble products. *KBE facilitates the capture of the intent behind the product design by representing the why and how in addition to the what of a design."*	Bailey [23]
"Knowledge Based Engineering is the execution of engineering tasks using knowledge that is not normally immediately accessible to the designer or engineer, and that has been purposefully accumulated and stored for use by the designer or engineer, usually (but not always) in some computer-mediated form. Thus, KBE usually (but not always) implies the use of some kind of computer system, examples of which include the so-called expert systems, web-based knowledge bases, and the like."	Pennoyer & Burnett [24]
Knowledge Based Engineering: *"The use of advanced software techniques to capture and re-use product and process knowledge in an integrated way."*	Stokes [25]

Table 2. Definitions on Knowledge Based Systems.

4 Knowledge Enabled Engineering Approach

Methods exist to capture and model knowledge, all with their advantages and disadvantages as seen in Table 1. Regardless what system/method is chosen, none will be the best in solving all problems. Knowledge Enabled Engineering (KEE) incorporates KBE and other knowledge rich strategies, where the KBE system normally works as the control center due to its demand driven ability. Conceptually, KEE can be explained in three steps: capturing of knowledge, automatization and quality control.

4.1 Capturing of Knowledge

In the area of Engineering Design, different kinds of knowledge assets embedded in the engineering design process exist. Different methods need to be used depending on the situation. The first step in the KEE approach is to map the process to be captured, which can then be used to choose what methods and systems are needed to capture it. When the best methods/systems that can capture the process have been identified, the process to follow begins.

4.2 Automation

In the end the idea is to automate the process captured. As with the first step different methods/systems exist here as well. By using KEE, the tools needed for each activity are identified. This phase is usually done simultaneously with the capturing of knowledge in the first step. It is an iterative process between the KEE system developer and the end user where the captured process can be shown and discussed.

4.3 Quality control

If the process is captured in a computerized system, it can be exactly repeated each time. Several hundred concepts can then be created where the process to generate and evaluate them is the same. This quality assurance gives the engineers a reliable basis to compare concepts. A captured process is now an asset of the company and can be reused whenever needed.

5 The Flange Design Process – KEE approach

To approach the research problem, the KEE approach was used, as demonstrated by capturing the knowledge within the engineering design process of a common machine element, i.e. two flanges joining two modules of an aircraft engine. A flange design process is relevant here since several elements from the entire life cycle affect the design and performance requirements. A study was conducted to find out what requirements engineers have on their processes. Project leaders and engineers from manufacturing, management and design departments were involved in the study, considered as representative for the process. A number of specific requirements were found in the study:

- Code should be system independent.
- The flange system must be adoptable as the flange is to be used as a part in other applications.
- User friendly graphical user interface.
- The system should support the engineers in their regular working environment.

A rotational symmetric flange joint constitutes an important function within jet engines, acting as an interface or link between different parts. It transfers loads while keeping the engine free from leakage. The bolts used in the flange joint have to keep the joint tight during engine operation. As always in design projects, several disciplines are involved to be able to create a product. Factors to be considered when designing a new bolt connection are loads, leakage and accessibility. The leakage problem is also dependent on the surface roughness between the two joining flanges, which is in turn dependent on the manufacturing process. The flange geometry is determined by geometrical restrictions from the surrounding components, but also on the fact that the flange shall be easy to assemble and maintain. One can quickly see that these areas are interlinked, see the example in Figure 1.

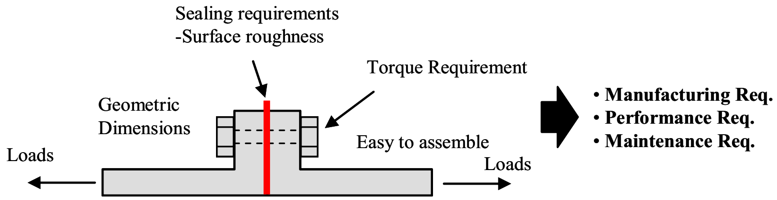

Figure 1. Section of a circular flange with its requirements and loads.

The figure also shows requirements to design the bolt connections flanges to fulfill all demands and safety criteria. The need for cooperation between the disciplines involved becomes obvious.

5.1 Design

The first step in the flange design process is to find the geometrical dimension needed to fulfill the function of the flange. This is calculated from the load requirements. The flange must withstand the loads transferred through the flange interface while preventing leakage. Some initial dimensional values must first be chosen, usually some values previously used on a similar flange with similar requirements. It now becomes possible to calculate if the bolt connection will withstand the applied load and prevent leakage.

5.2 Manufacturing

When the geometrical dimension and tolerances needed are set, a plan on how to produce the flange can now be created. A team of manufacturing engineers, weld technicians or other experts will define a suitable manufacturing process. The team creates an operation list describing each manufacturing operation, including the manufacturing time.

5.3 Maintenance

The flange acts as the interface between different components and its design will affect 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.

5.4 Cost Report

An operation list is needed to create a manufacturing and material cost report. This operation list is defined in the "Manufacturing" section. Each operation is performed in a machine. From the time cost of the machine and the time to perform each operation, the manufacturing cost is calculated. To create a KEE application that can support the engineers, knowledge from each of the phases described above is needed.

5.5 Knowledge Acquisition

When this phase starts the purpose of the application is set, i.e. to create an application that can support the flange design process. A natural step is to then start knowledge capture from the flange design process. This phase is critical for the success of the entire application and the amount of time allotted here will save time later. As described in the flange design process section, the required knowledge comes from the areas of design, manufacturing, maintenance and cost reporting. Of note is that the different areas represent different stages in the development process and the product's life cycle. The company's design instructions describing the flange design process, and interviews with those involved in the process constitute the basis behind the extracted knowledge presented below. This section will give some examples from knowledge of the flange design process in the four disciplines: design, manufacturing, maintenance and cost reporting. This knowledge will be used in the following examples to make understanding the structure behind the application easier.

5.5.1 Design Process Knowledge

As described earlier in this section the engineer needs to design the geometric dimensions of the flange. The process contains a number of steps, the first of which is to assume some geometrical dimension, i.e. number of holes, bolt dimensions, etc. From these assumptions, a number of calculations yield information such as nominal bending forces in bolt and flange minimum and maximal pre-stressing forces due to friction within threads and between contact surfaces calculate the maximum force before bolt separation etc.

One step in this process is to calculate the maximum force before bolt separation. This is done with the following equation:

$$\text{Maximum bolt force before separation} = \frac{\text{Prestressing Force Lower - Minimum residual prestressing force - Residual prestressing force due to composing}}{1 - \dfrac{\text{Bolt Stiffness}}{\text{Bolt Stiffness} + \text{Flange Stiffness}}} \quad \text{(Eq. 1)}$$

This is a rather iterative process and several parameters can be changed by the engineer, therefore providing a number of alternative solutions that can fulfill the requirements.

5.5.2 Manufacturing Process Knowledge

To define the manufacturing process a geometric representation of the product is needed. In this case, a circular flange geometry with a number of holes. The next step is to choose a manufacturing process. The information needed to manufacture the flange is heavily dependent on other parameters such as choice of material, the amount of material to be removed, wanted tolerances, machine availability needed to manufacture the component in terms of power, number of axles etc. This phase can be affected by the design process and the tolerances chosen will affect manufacturing operations. Even the shape of the geometry can affect accessibility and the time to produce the wanted surface. When the manufacturing process is defined, calculating the total manufacturing time is rather straightforward. One step in this process could be to calculate the cutting time for a turning operation, done with the following equation:

$$\text{Cutting time} = \frac{\text{Area}}{\text{Feed per revolution} \times \text{Cutting speed}} \quad \text{(Eq. 2)}$$

Manufacturing knowledge is also well documented in different handbooks and via the professional experience of manufacturing engineers.

5.5.3 Maintenance Process Knowledge

A geometrical representation is also needed to design the maintenance process. The geometry is used to consider tool accessibility during the assembling and dismantling phases. One step in this process is to find the assembly time for all bolts, defined using with the following equation:

$$\text{Total Bolt assemble time} = \text{Number of bolts} \times \text{Single Bolt assemble time} \quad \text{(Eq. 3)}$$

5.5.4 Cost Report Knowledge

In the sales process information such as material costs, production lead times, processes used, etc., is needed to calculate (or predict) the total cost of the finished product. The gathered information is often entered into different types of spreadsheet computer programs, in this case a spread sheet is used for manufacturing and material cost estimations. Before the Excel sheet can be executed, the correct information must be entered, such as operation lists etc. This is presently done manually with the user of the Excel sheet typing in operation numbers and the calculated time for each operation.

5.6 Knowledge Formalization

The acquired knowledge has to be translated into a reusable form, as seen in Table 3. The first column 'Service description' describes the name of the class or object to contain the knowledge. Knowing where to place all the information and how to structure it properly can be initially difficult. Therefore, one can give the class a somewhat more general name to represent the knowledge and then change or rearrange the information later. The column 'Parent' addresses the parent class. The column ‘Property’ gives names of the rules in the class. These names should be unique and represent what action or task the rule performs. The column ‘Source’ specifies the kind of source for the rules. Some rules may be user defined, since the finished system is supposed to work interactively with the user. Properties defined by rules like “1.5 * Bold_Head_Diameter” is called rule. In the last column called “Rules”, all the rules are outlined and their interactions between each other can be followed.

Service Description	Parent	Property	Source	Rules
1.1.2 Bolt_Analysis_CLASS	1.1.1	1. Bolt Clearance 2. Hole Centre to Tip 3. Bolt Type 4. Lubricant ... 16. Bolt load 17. Max. Bolt Force Separation ...	1. Rule 2. Rule 3. User 4. User ... 16.Rule 17.Rule ...	1. Bolt_Clerance = 1.5 *Bolt_Head_Diameter 2. Hole_Dentre_to_Tip = 1.5 *Bolt_Head_Diameter 3. Bolt_Type = User Defined 4. Lubricant = User Defined ... 16. Bolt_Load = Line_Load_at_Bolt / Number_of_Bolts * Pi * 2 * (Flange_Mantle_Middle_Radius + Middle_Mantle_to_Hole_Centre) * (Bolt_Stiffness / (Bolt_Stiffness + Flange_Stiffness))) 17. Max_Bolt_Force_Separation = (Prestressing_Force_Lower - Min_Residual_Prestressing_Force – Residual_Prestressing_Force_Composing) / (1 – Bolt_Stiffness/ (Bolt_Stiffness + Flange_Stiffness))
1.2.2 Turning_Manufacturing_CLASS	1.2.1	1. Material Add Factor 2. Material 3. Surface Roughness 4. Cutting Area 5. Feed per Revolution 6. Cutting Speed 7. Cutting Time	1. User 2. User 3. User 4. User 5. Rule 6. Rule 7. Rule	1. Material_Add_Factor = User Defined 2. Material = User Defined 3. Surface_Roughness = User Defined 4. Cutting_Area = User Defined 5. Feed_per_Revolution = f(Material, Surface_Roughness) 6. Cutting_Speed = f(Material,Surface_Roughness) 7. Cutting_Time = Cutting_Area/(Feed_per_Revolution*Cutting_Speed)

Table 3. Captured knowledge translated into a computer readable form.

6 Modeling downstream activities using KEE

When the flange design process has been captured and formalized it is time to define the structure and start coding the application. At this stage, the process becomes slightly affected by what tools are available at the site. This aerospace manufacturer specializes within aircraft and space components. It is a conservative business with many requirements from governments and their product development partners. Tools used to automate activities in the flange design process are products from Unigraphics Solution (UGS) and Microsoft. Inside Unigraphics (UG), a KBE module called Knowledge Fusion (KF) is found. This modeling technique, see Table 2, will work here as the control center for the KEE application.

6.1 KEE application structure

All elements from the formalized knowledge are named and addressed. The structure of the flange design application is then outlined. This step is extremely important and requires careful reflection. Here, outlining the structure in a way that will allow the flange design process to be followed by the user is critical. Activities to create geometry, structural analysis, manufacturing analysis, maintenance analysis and report become holding blocks of the knowledge, see Figure 2. This enables a clear presentation of the relationships between objects; the more complex objects in the structure are built by other simpler objects. Each activity is eventually captured in an object.

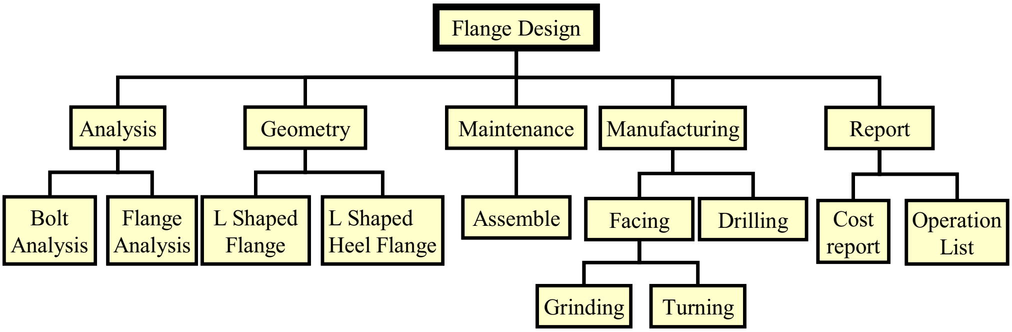

Figure 2. The structure of the flange design application.

6.2 Coding the application

Each object in the structure is used as a holding block for the captured process and is defined by its class. For example, knowledge about the "maximum bolt force before separation", as described in Eq. 1, is now represented in a parameter called 'Fsep' defined inside the 'Bolt Analysis CLASS'. Running the object 'Bolt Analysis' and asking for the parameter 'Fsep' will automatically calculate the value of 'Fsep'. To create the report in the Sales process, data from the manufacturing process is entered in a spread sheet. This process is now automatically done in two steps, i.e. the manufacturing information is dumped into an Access database and Visual Basic is used to create an operation list inside the Excel sheet with operation numbers and the time for each operation, all extracted from calculations done in Knowledge Fusion.

7 Example of the KEE application usage

Figure 3 presents the information flow of the KEE application. Five main blocks are used to describe the main activities, i.e. product definition, performance evaluation, manufacturing evaluation, maintenance evaluation and cost report generation. The example in the following sections describes how the flange design application works. The system used also provides a tool for designing user interfaces, which has been used to create the interfaces shown in the Figures 4 - 10.

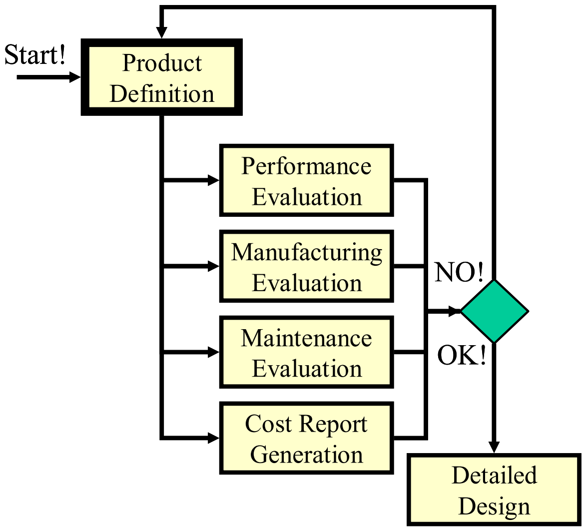

Figure 3. Information flow in the KEE application.

7.1 Product Definition

The interface in Figure 4 is presented when the application begins. The user can now define known properties such as flange type, flange location, radius, etc. Two geometries are generated to illustrate an example of a topological change. For the second geometry, the heel is removed and the flange is automatically adjusted, Fig. 5. From this interface the user can go down and specify properties for Design Evaluation, Manufacturing Evaluation and Maintenance Evaluation or just toggle on the white box next to Generate Report to generate the cost report.

7.2 Performance Evaluation

An important requirement for flanges is to prevent leakage with the proper bolt joint. It is also crucial to keep the bolt stress under the yield limit. If the specified limit is reached, the application alerts and suggests a change of bolt material or bolt size or both, Fig. 6. When a new bolt is chosen the geometry is adapted to enable easy bolt change, which is an example of a maintenance rule used in the design evaluation process.

7.3 Manufacturing Evaluation

Manufacturing properties considered in this application are facing and drilling. The type of facing operation is governed by the given planar tolerance for the surfaces to be faced, A1 – A3, Fig. 7. Depending on the chosen tolerance, either turning or grinding is given as a suitable technique. Changing the surface roughness of the finished product is also possible. The tooling time for these operations is continuously calculated as changes of these parameters are made. The cutting time in Fig. 7 shows the result from the manufacturing process knowledge stored in Eq. 2. Drilling is evaluated using the user interface shown in Fig. 8. Depending on the chosen bolt diameter, accessible tolerances for positioning the hole are shown. The total drilling time can also be seen in the interface.

7.4 Maintenance Evaluation

The maintenance interface is shown in Figure 9. The value of Eq .3 is calculated and shown in the interface under the name ‘Total Bolt Assembly Time’. Changing bolt type may affect the time for each bolt change and change the number of bolts around the flange. The effects of changing bolt type or new flange dimensions will be shown directly in the maintenance interface.

7.5 Cost Report Generation

When the user is satisfied with the generated concept, a cost report can be generated. Creating a report is optional by toggling the ’Generate Report’ box in the interface shown in Fig. 4 and pushing the ’OK button’. The application will then ask for all parameter values in the defined concept. Each parameter value will then be dumped into an Access database. A visual basic script is then trigged. This script will start to search the database for all parameters with the necessary data in the operation lists. When the data are found an operation list is created inside the Excel sheet used for cost estimation, Figure 10.

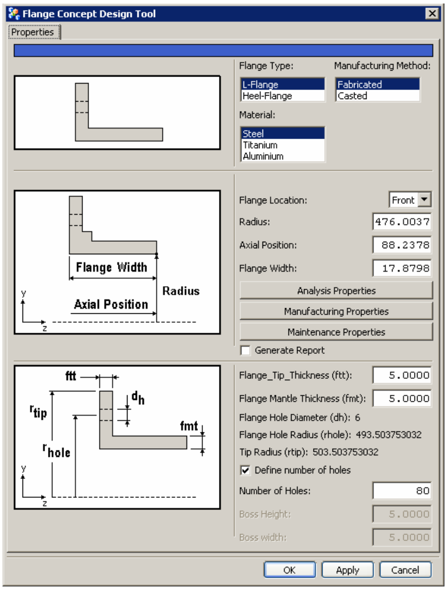

Figure 4. Main user interface of the KBE application in UG.

Figure 5. A topological change is made where the user removed the heel from the flange geometry.

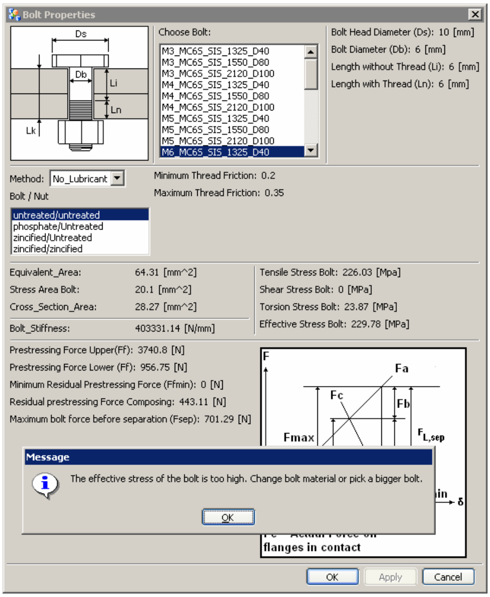

Figure 6. The application alerts if the chosen bolt is unsuitable.

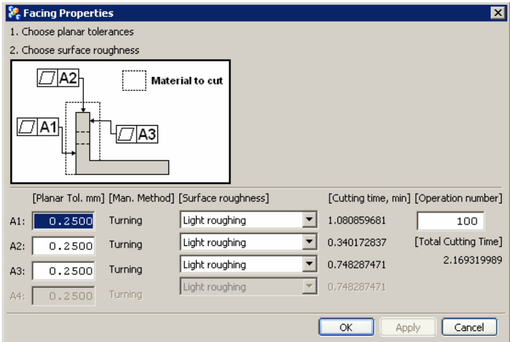

Figure 7. Facing evaluation.

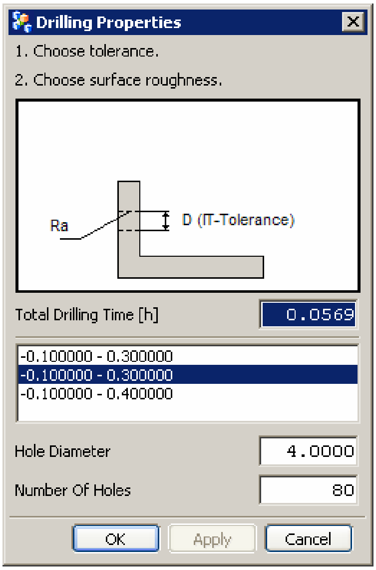

Figure 8. Drilling evaluation.

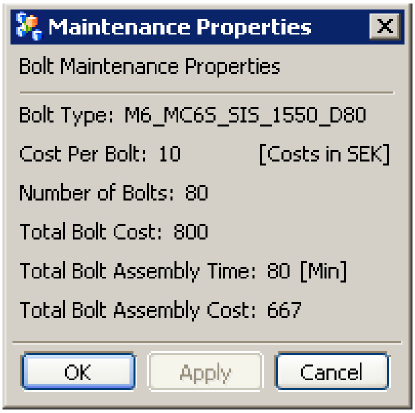

Figure 9. Maintenance properties.

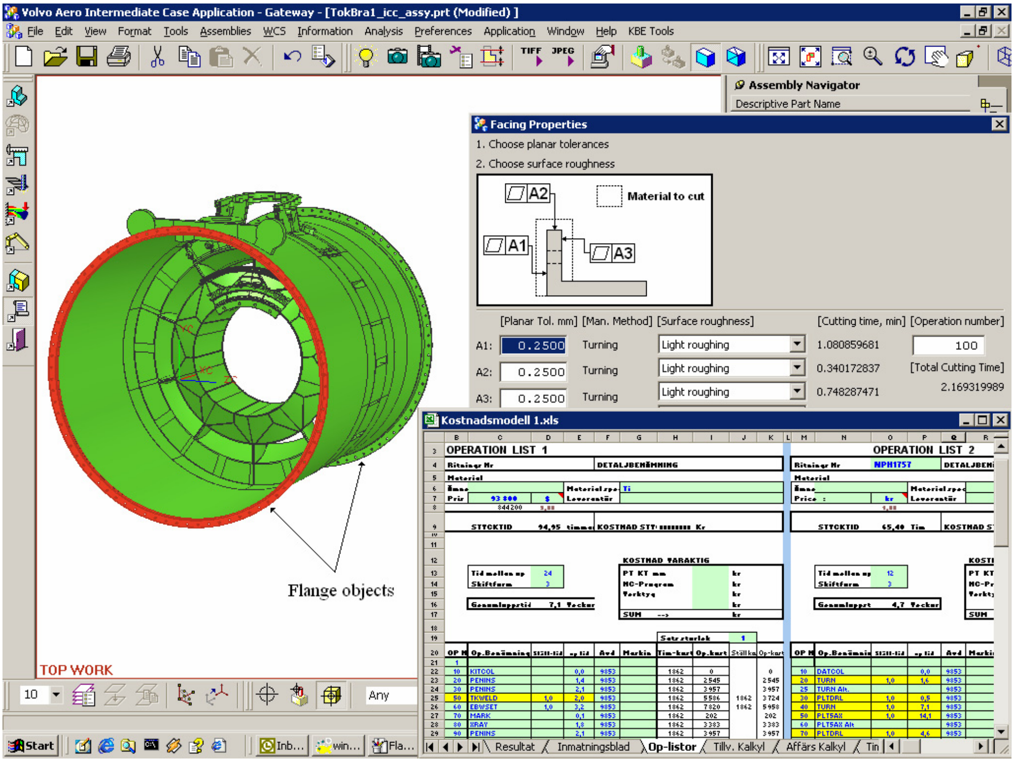

Figure 10. The flange KEE application coupled to an engine component. The cost report is shown in the lower right hand corner.

8 Discussion

Difficulties in working with a specific system due to a lack of functionality have trigged the development of this new knowledge modeling technique KEE. This technique allows the user to choose what system or tools to use for a specific task. The KF application (version 18) did not support manipulation of an Excel sheet as an example, which was then solved by using a script in visual basic. Still, the demand driven ability of the application was retained by using KF as the control center of the flange design application. A controlled quality is achieved by working according to this KEE approach. By capturing the actual process, it can be duplicated indefinitely. The modeled process becomes an asset to the company, allowing it to be used when needed to extract knowledge for decision-making of new concepts. The usability of knowledge modeling techniques is further extended. Objects holding a different task solved by different methods and tools are now building the process. When a better way of solving a task is found, changing the object holding the task is easy. What tool or method to use in each object can now be changed or modified to improve the captured task in the overall process.

It has been shown that by using this KEE approach, it becomes possible to support the conceptual flange design process by making available downstream elements with both hardware and service knowledge. This allows engineers to work less with routine tasks and focus more on innovative work to optimize life cycle properties. Maintenance represents one of the later stages in the product life cycle, though it affects the design phase and overall cost. It also affects the tool cost because the geometry can be adapted to standard tool sizes and for easy access. In this KEE application the manufacturing method, tolerance and surface finish, and the correct manufacturing operations can be altered, giving the engineer a direct response of how much the chosen method, tolerance, etc., will affect the manufacturing and maintainability costs. When a product is developed traditionally, these aspects are not seen until the product specification or geometry reaches the production and maintenance department. When the manufacturing cost is calculated, the data used as input in the interface can also be used as input for other calculations and operations, e.g. if the manufacturing preparation process is further integrated with the KEE application the choice of tolerance and type of manufacturing process can control the creation of NC-tool paths.

The geometry and report generated from the KEE application can also be used as a common decision tool, allowing people from different ED disciplines to discuss what actions to take. The KEE application explained in this article should be viewed as a part of a larger project where other KEE applications are developed and used to support the design process of jet engine components.

When entire processes will be captured in this kind of support system they become valuable assets to the company. Internal assets such as knowledge and experience of how to develop and produce the product are considered confidential by the company. How should we handle these new knowledge dense systems, such as KBE, especially when companies want to cooperate and benefit from the ability to design the life cycle properties of future products? Another problem for future research is to set the right requirements on the overall KEE system. If wrong requirements are used, the sub system becomes unreusable without major restructuring efforts.

9 Conclusion

The application presented in this paper shows how downstream activities can be modeled using KEE, as demonstrated by conceptualization of a mechanical element with different performance and life cycle requirements. This will allow engineers to do less routine work and utilize their time to optimize the life cycle properties. In this KEE application the manufacturing method, tolerance and surface finish, and the correct manufacturing and maintenance process number can be altered, providing the engineer a direct response of how much the chosen method, tolerance, etc., will affect the manufacturing and maintainability costs. When developing the product in a traditional way these aspects are not seen until the product specification or geometry reaches the production and maintenance department. This kind of KEE application will allow simulation of the product life cycle to predict the operative cost. Early knowledge about the operative cost will be the key factor in strategic decisions for business cases such as total offers.

10 Acknowledgement

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Paper C

INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
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A DESIGN TOOL INTEGRATING CAD AND VIRTUAL MANUFACTURING FOR DISTORTION ASSESSMENT

Marcus Sandberg, Peter Åström, Tobias Larsson and Mats Näsström

Abstract

In the aerospace industry, predicting the effects of the initial manufacturing method, often casting or forging, and that of machining on component distortion is crucial to avoid components being wasted due to the failing of required geometric tolerances. This since both forging and casting introduce unwanted stresses in the component that in subsequent machining stages could be a source of distortion. The design tool in this paper couples the simulation of distortion effects due to machining with CAD, where knowledge of how to perform a machining simulation is captured within the tool. The tool system is governed by a UNIX shell script and uses Python scripts for pre- and post-processing purposes coupled to the finite element software MSC.Marc™. The tool allows an engineer to estimate the distortion effects due to machining and is believed to help bridge the gap between design and computational engineers in the manufacturing planning stages of engineering design. By using tools like the one presented here, both component quality and accuracy of machining operation cost estimation can be expected to increase, since distortion problems can be solved or prevented already in the manufacturing planning stages of engineering design.

Keywords: Knowledge Enabled Engineering, Finite Element Analysis, Design Support, Virtual Manufacturing, Machining Distortion.

1 Introduction

Researchers dealing with analysis and researchers active within the engineering design discipline believe in a trend towards a more extensive use of Finite Element Analysis (FEA) among designers as an aid in engineering design activities [1] [2]. Knowledge enabled engineering complies with this trend as a method to integrate product development activities such as engineering design and analysis.

In the aerospace industry and specifically in jet engine component manufacturing, machining operations are common. Forging and casting operations are often used to manufacture the initial geometry. Both of these processes introduce unwanted stresses in the component, and might be a source of distortion in subsequent machining stages. Hence, predicting the effects of the initial manufacturing method (casting or forging) and that of machining on component distortion is crucial to avoid components being wasted due to failure to achieve the required geometric tolerances.

Computer aided engineering for design and analysis has been recognized as important for product development activities, e.g. [3]. Some efforts have been done to integrate design and performance analysis, e.g. [1] [4]. Bathe [2] states that the reason why a designer uses analysis in the first place is a desire to somehow enhance the product characteristics. Hence, designers are not interested in the underlying principles of FEA. Therefore, Bathe predicts a more integrated use of FEA in Computer Aided Design (CAD) software with easy-to-use interfaces, where the knowledge of how to perform a specific analysis is embedded in the software.

Analyzing the effects of manufacturing on the component in terms of component properties, such as stress levels, distortions, etc., will here be referred to as virtual manufacturing. The work presented in this paper is an effort to couple virtual manufacturing and specifically machining distortion predictions with CAD in a design tool where knowledge about how to perform a cutting analysis is captured in the proposed system.

2 Recent work

Knowledge based engineering (KBE) has emerged during recent decades as a popular way of supporting design tasks. It is commonly claimed that the benefits of KBE are greatest if the product change from one product in the product family to the next is minor. KBE is also preferably used for routine design tasks where a designer makes knowledge-based decisions on a daily basis. The increase in engineering productivity through the use of KBE results in tedious, time consuming, error prone and repetitive tasks being automated [5]. There are also examples of KBE being applied to structural analysis where the goal of merging KBE and analysis ranges from automation of meshing tasks to the automatic application of boundary conditions [4]. Other applications range from damage tolerance design of aircraft bodies [6] to configuration and finite element analysis of aircraft composite designs [7]. The focus of most research combining KBE and analysis is still to either automate the creation of an analysis model from the real product geometry [1] or use KBE to automate the translation of the real load case (or environment) into model boundary conditions. Either way, the knowledge captured relates to how reality should be translated into a computational model or, as stated by Chapman [5], storing the how, why and what of a design.

Little research exists where the potential of merging KBE and non-linear finite element analysis is investigated. The type of knowledge captured in the design tool can be claimed to be independent of the product, since it can be applied to any product being machined. It is also a way of enabling designers with little or no computational background to perform finite element analyses rationally and cost efficiently.

3 The Design Tool

Using knowledge enabled engineering (KEE), a design tool connecting CAD and distortion assessment using FEA was developed. The design tool consists of CAD software coupled to finite element software (MSC.Marc™) by means of Python and UNIX scripts. The design tool is controlled through a graphical user interface.

3.1 Knowledge enabled engineering

Using knowledge based engineering as a point of departure, KEE is here in focus. KBE often associated with commercial software [8] rather than as a method for engineering design knowledge reuse motivates this new definition. KBE applications also often focus on utilizing a CAD environment rather than employing a wider range of engineering design methods (which may include CAD). With KEE, engineering design, KBE and similar knowledge intensive methods are included [4], to enable by any means engineering knowledge for the user of the engineering design support tool.

3.2 Tool overview

The design tool is schematically depicted in Fig. 1. A flange geometry definition is generated using the graphical user interface (GUI). By setting cutting depth, cutting order and direction, the finite element simulation can be initiated through the GUI. Scripts that collect mesh properties and state variables from a preceding simulation file manage the rest of the procedure. The preceding simulation file contains information about the component process history, such as the residual state after casting or forging in terms of stress, strain, equivalent plastic strain and displacements. Together with an MSC.Mentat™ macro (macro 1), the Python script performs preprocessing. When preprocessing is finished, the macro starts a UNIX shell script that in turn starts MSC.Marc™, and stops the finite element simulation after the first increment to enable a Python script to adjust the mesh to fit the tool path defined in the GUI. The cutting simulation continues and utilizes Fortran 77 subroutines. When the simulation is finished the resulting distortion is communicated back to the GUI through an MSC.Mentat macro (macro 2). Python and UNIX scripts are chosen because no additional software is required to write the scripts since Python is freeware and the ability to write UNIX scripts is included in the operation system. Fortran code is the only subroutine language in MSC.Marc and the industry partner uses both the CAD-software and the finite element solver.

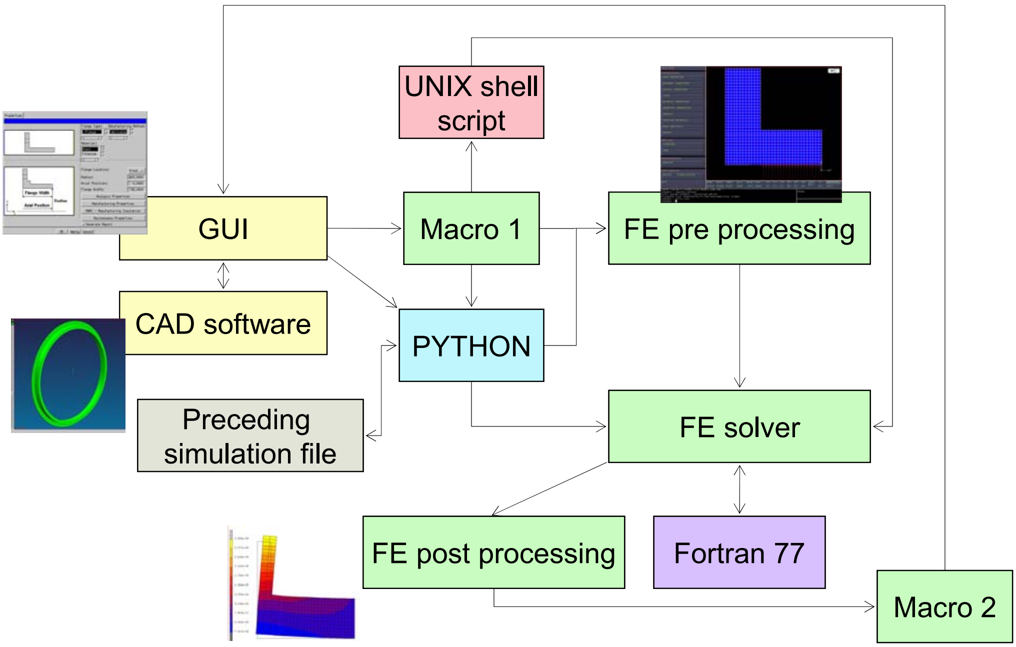


Figure 1: The design tool system layout.

3.3 Graphical user interface

Graphical user interfaces are used to control both the geometric design and the distortion assessment, see Fig. 2. The left window in Fig. 2 shows the main interface where the principal flange geometric parameters are set. The process parameters in the right window are supplied by choosing the number of cuts, cutting order and cutting direction. Cutting direction can be either in a positive or negative x or y, depending on the cut side.

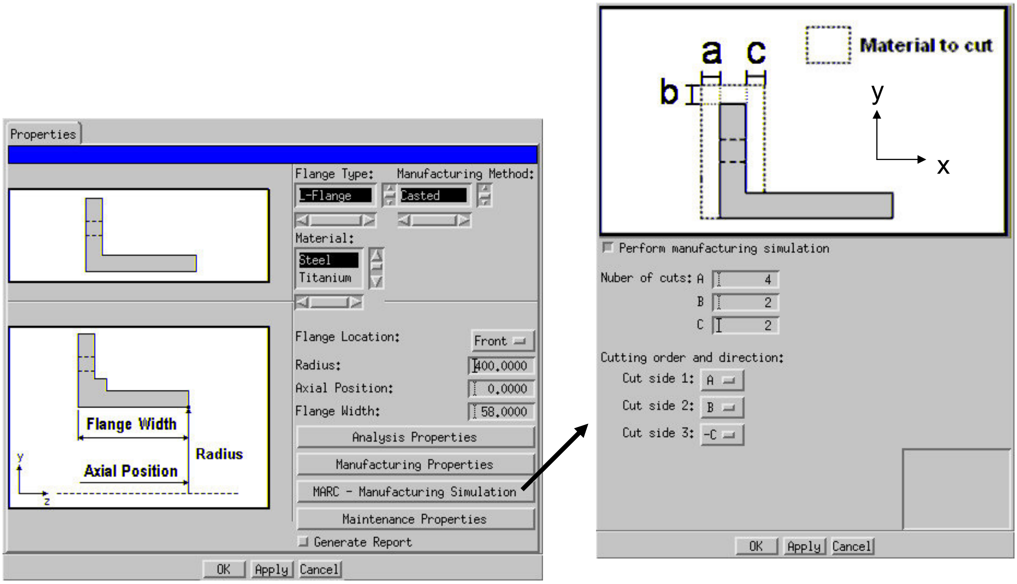


Figure 2: GUI for specification of geometry and machining process parameters.

3.4 Machining Distortion Assessment using an Element Deactivation Technique

The element deactivation technique used to simulate the effects of machining on component distortion is a computationally efficient technique where it is possible to analyze longer machining sequences. Simulating mechanical cutting by using traditional contact analysis is demanding computationally due to a number of factors, e.g. extremely high strain rates, complex changing contact conditions and the need for continuous remeshing to capture the cutting chip evolution. These factors negatively affect the computational times to the extent that using contact analysis as a tool for distortion assessment, when a complete cutting sequence is to be analyzed, is simply too time consuming. Contrary to the element deactivation technique, contact analysis considers several physical phenomena, such as heat generated due to both friction and plastic deformation in the workpiece material.

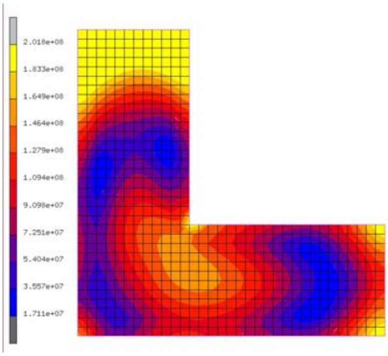
However, during smooth machining conditions, approximately 80% of the generated heat is removed from the process with the chip [9], thereby motivating the use of techniques such as the element deactivation technique. The plasticized layer of material introduced by local material deformation between the tool and the workpiece only has a thickness of several hundred microns [10], i.e. the plasticized material from one tool pass is removed in the next. Hence, if distortion is the focus of the analysis, the use of the element deactivation technique as a tool for distortion assessment is hereby motivated.

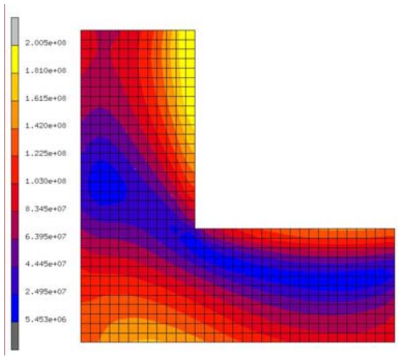
The principal underlying assumptions of using the element deactivation technique is that the removal of material with certain stiffness and a certain residual stress state causes the majority of distortions. The removal of this material is reflected in a distortion of the component when it returns to a new equilibrium state.

4 Results from Design Tool Testing

The design tool was tested on machining of flange geometries typically found on axisymmetric components in a jet engine. Flange joints are often used to connect one component to another within the engine, where tolerance requirements on the flange in terms of the mating surfaces being parallel to one another are strict. In addition, flange geometries are simple and, therefore, suitable for the testing of design tool principles.

In the scenario described here, the designer can choose between two semi-finished starting materials, one forged and one cast. The designer intends to investigate whether a casting or a forging is appropriate in manufacturing a flange with certain dimensions. Further, the aim is to determine if the machining sequence influences the distortion and what the final distortion is for two different machining sequences.





a) **b)**

Figure 3: a) Residual Von Mises stress state from previous forging operation [Pa]. b) Residual Von Mises stress state from previous casting operation [Pa].

Figure 3 shows the initial states in terms of residual stress (Von Mises) resulting from the initial manufacturing method and prior to machining.

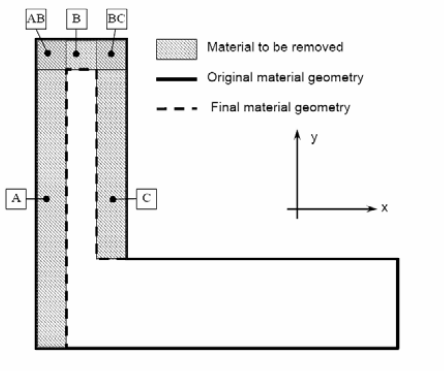


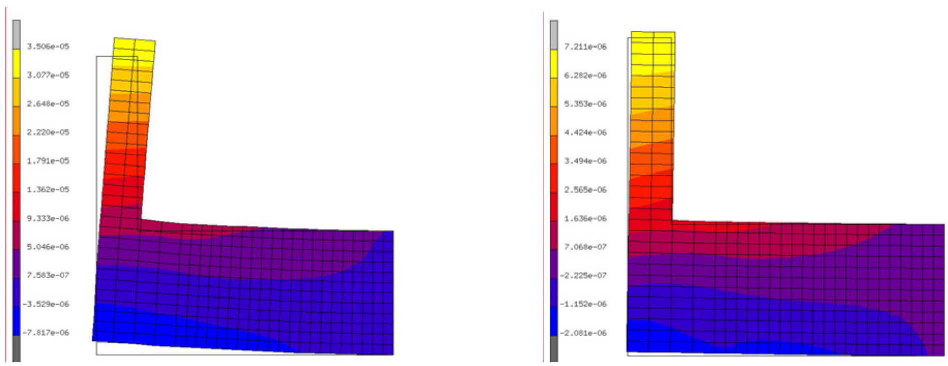
Figure 4: Material to be removed by machining.

The influence of distortion on two machining sequences has been investigated. The machining orders for these cases are listed in Table 1 along with the number of machining passes to remove the material in each area: A, AB, B, BC and C, all visible in Fig. 4. Table 1 indicates the machining direction with a [+] or a [-], referring to the coordinate system visible in Fig. 4.

It is implied that machining of areas A and C is done in either a positive or negative y-direction while machining of area B is performed in either a positive or negative x-direction.

Table 1: Machining sequence I and II. The prefix denotes the number of machining passes made while A, B, and C refers to the areas visible in Fig. 4. The [+] or [-] denotes the machining direction according to the coordinate system also shown in Fig. 6.

	I	II
1'st area to be machined	4x (A[+], AB[+])	2x (BC[-], C[-])
2'nd area to be machined	2x (B[+], BC[+])	4x (A[+], AB[+])
3'rd area to be machined	2x (C[-])	2x (B[+])



a) **b)**

Figure 5: a) Final x-distortion [m] after component being machined out of a forging (Distortion magnified 100x) b) Final x-distortion [m] after component being machined out of a casting (Distortion magnified 100x).

Figure 5 illustrates the minimum x-distortion obtained if casting produces the initial component geometry. For casting, the x-distortion due to machining is a factor 20 less than that of a forged initial geometry.

If casting is chosen as the initial manufacturing method, the influence of altering the machining sequence can be seen in Fig. 6. From Fig. 6, machining according to sequence I in Table 1 produces the x-distortion history visible as the solid line, while machining according to sequence II produce the x-distortion history visible as the dotted line.

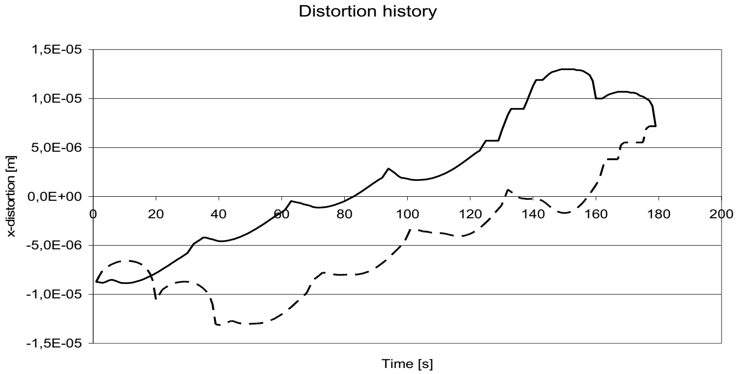


Figure 6: a) Distortion history in the case of machining in accordance with the sequences listed in table 1. The solid line represents machining sequence I, while the dotted represents sequence II. Shown is x-distortion [m] as a function of time [s] for the two cases.

5 Discussion

The design tool presented herein has been tested in two scenarios. The initial residual states before machining differ in one scenario, while the machining sequence differs in the other.

In the scenario described here, where the focus is to minimize distortion due to machining, choosing casting as an initial manufacturing method seems to be preferable. The influence of machining order is determined by investigating two machining sequences (see Table 1), though altering the machining sequence does not affect the final result in this case. The final distortion after all machining passes is the same regardless of the machining sequence. Therefore, the best way of obtaining the final geometry among the investigated cases is by choosing a casting, while the order of machining has no influence on the final distortion result.

The results indicate that the tool can be used for rapid distortion assessment in concept stages of product development. An advantage with a design tool like the one presented is that a designer could in fact perform part of the computational work traditionally performed by computational staff, because no or little FEA knowledge is needed for a user to submit an analysis and estimate distortion. The possibility to account for how the component will be manufactured already in the concept development phase increases the potential for savings in later stages of the product development process, since manufacturing planning rework could be expected to decrease.

No required FEA knowledge to perform a simulation also implies a risk for the so-called black box phenomenon where the user does not understand what is really being done when an analysis is performed. The authors believe that this can be avoided if cross-functional teams are formed with computational engineers and designers working together in the introductory phase. Computational engineers who are assigned system development responsibility would benefit from the cooperation by learning how designers work and thus how the system or tool should be designed to support their working principles. The designers would in turn benefit by learning more about what computational procedures are performed when submitting an analysis. In this sense, the gains for both categories of personnel are mutual. The authors also believe in the importance of system transparency, by allowing the user to understand what happens when something goes wrong, and promote as much self-learning as possible. The roles of the designer and computational engineer could change if KBE systems with manufacturing simulation possibilities were introduced as concept development tools. The designer would get the role of a design analyst while the computational engineer could gradually get more of a support function in the concept phases of product development.

Using the element deactivation technique to simulate the distortion effects is, compared to simulating certain other manufacturing processes, one that is computationally easy. In contrast to processes where large thermal or mechanical gradients, intermittent contact or other severe non-linearities are found, the non-linearity is mainly due to material non-linearity. User intervention when simulating, for instance, welding is expected to be greater to enable the process to be simulated. An increasing level of necessary user interaction also increases the difficulties with an implementation in a knowledge system. It would therefore be of great interest to investigate the possibility to implement other manufacturing process simulations in knowledge systems.

6 Conclusion

The tool helps in bridging the gap between design engineers and computational experts when analyzing machining operations. It can also serve as an aid in the manufacturing planning stages of engineering design, since the influence of machining parameters such as machining order or cutting depth on component distortion can be determined with little knowledge of FEA. By enabling predictions of machining distortion to be done early in the product development process, the process understanding increases and the errors involved with cost assessment of manufacturing operations are reduced. The component quality can also be expected to increase, since distortion problems can be solved or prevented already during the manufacturing planning stages.

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