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A DESIGN TOOL INTEGRATING CAD AND VIRTUAL MANUFACTURING FOR DISTORTION ASSESSMENT

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Abstract

In the aero space industry, design for manufacturing promotes machining predictions using finite element analysis during design. Today design and computational engineers often are far from integrated. 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. Thus design for manufacturing is enhanced since redesign due to inferior manufacturing can be reduced.

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

1 Introduction

Design for manufacturing involves predictions to minimize poor manufacturing due to design flaws. The aerospace industry aims to predict component distortion due to machining using finite element analysis (FEA). Currently there is a gap between design and computational engineers why machining prediction using FEA is time demanding since a designer has to define the problem, submit it to a computational engineer and wait for the results. Thus designers often omit FEA simulations. Researchers dealing with analysis and researchers active within the engineering design discipline however 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 an approach to integrate product development activities such as engineering design and analysis to improve design for manufacturing.

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. Thereby engineering designers are enabled to perform manufacturability simulations during early design.

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 for manufacturing simulation 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 is an extension of the multidisciplinary tool presented in [8] and 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 product 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.

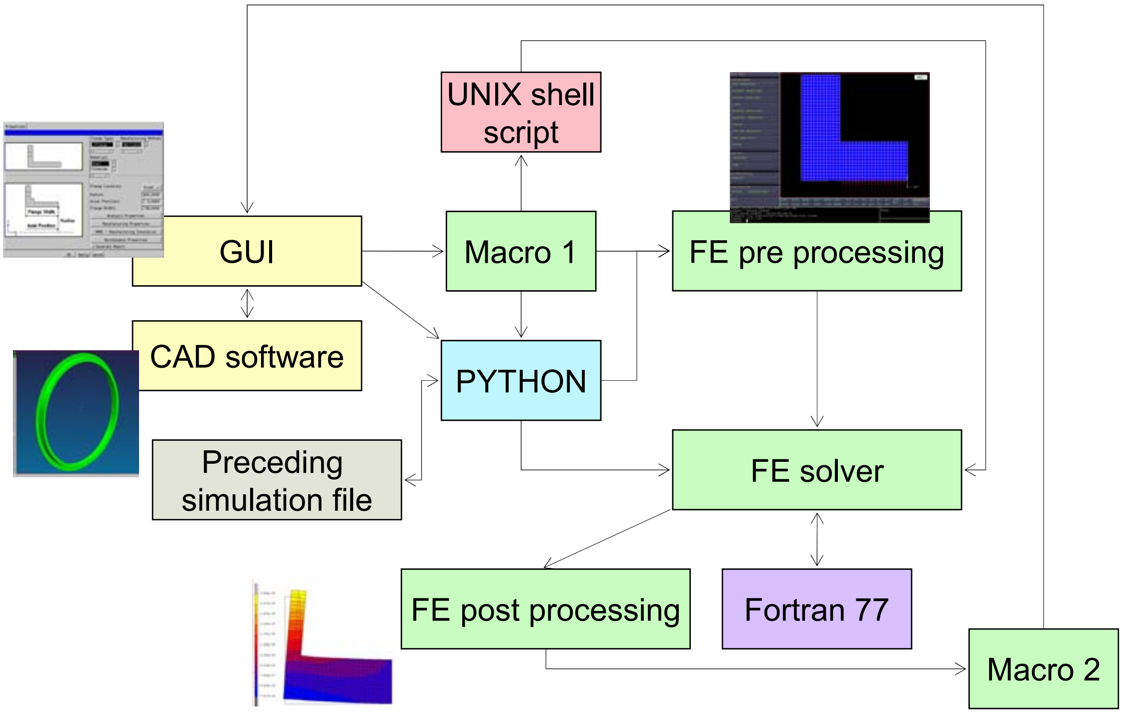
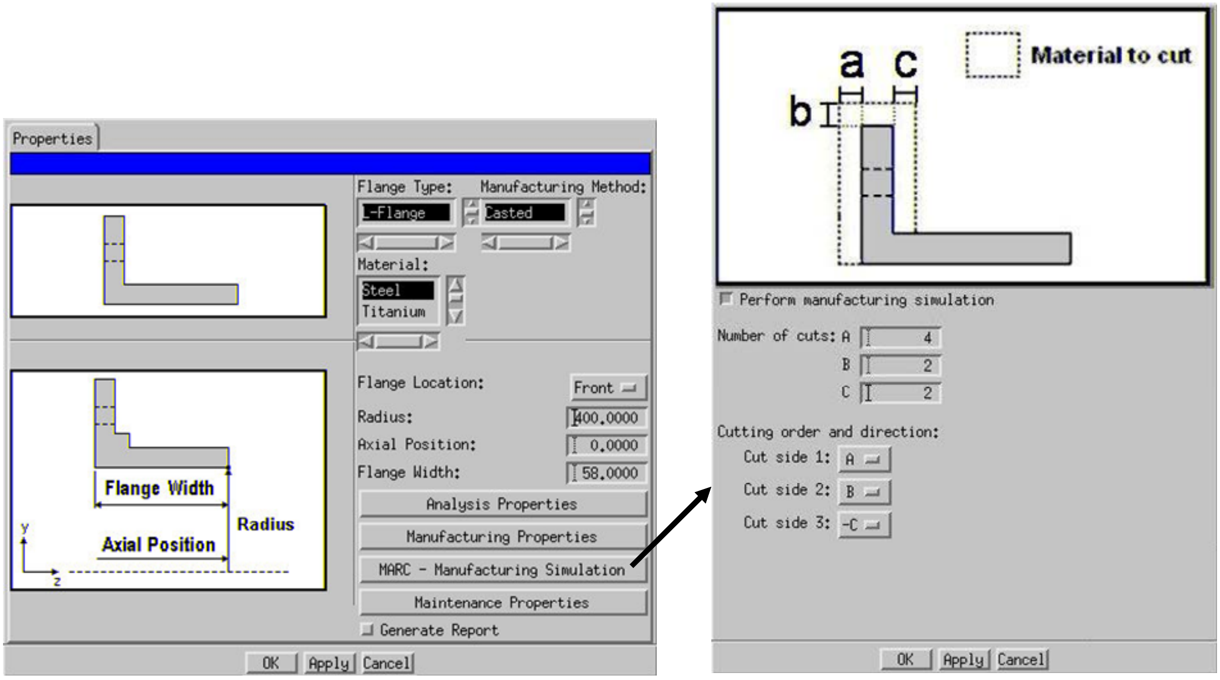


Figure 1: The design tool system layout.

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.


Flange Type: L-Flange
Manufacturing Method: Casted
Material: Steel
Flange Location: Front
Radius: 400.0000
Axial Position: 0.0000
Flange Width: 58.0000
☐ Generate Report

☐ Perform manufacturing simulation
Number of cuts: A 4
B 2
C 2
Cutting order and direction:
Cut side 1: A
Cut side 2: B
Cut side 3: -C

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.

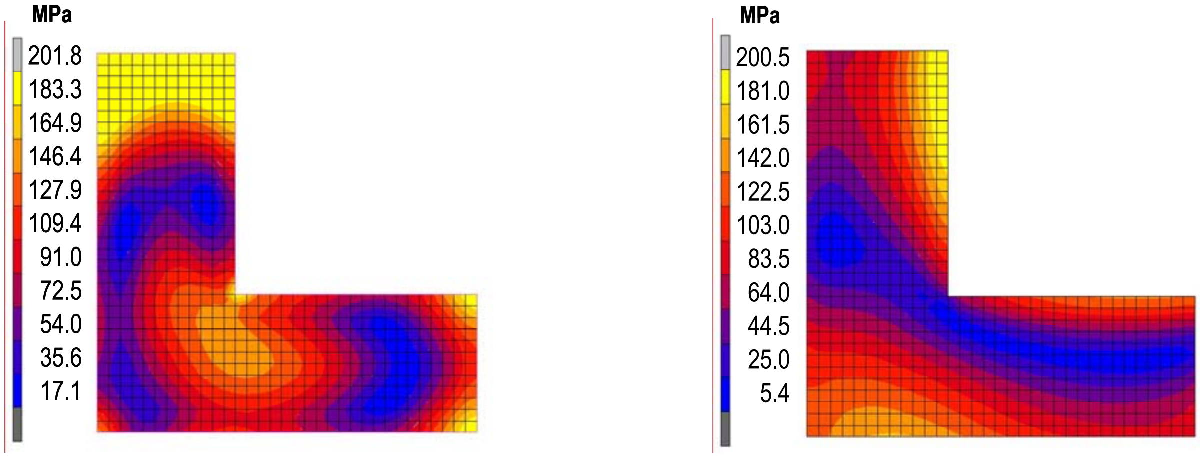
However, during smooth machining conditions, approximately 80% of the generated heat is removed from the process with the chip [10], thereby motivating the use of techniques such as the element deactivation technique. The plasticized layer of material introduced by local material deformation between the tool and the workpiece only has a thickness of several hundred microns [11], 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. b) Residual Von Mises stress state from previous casting operation.

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

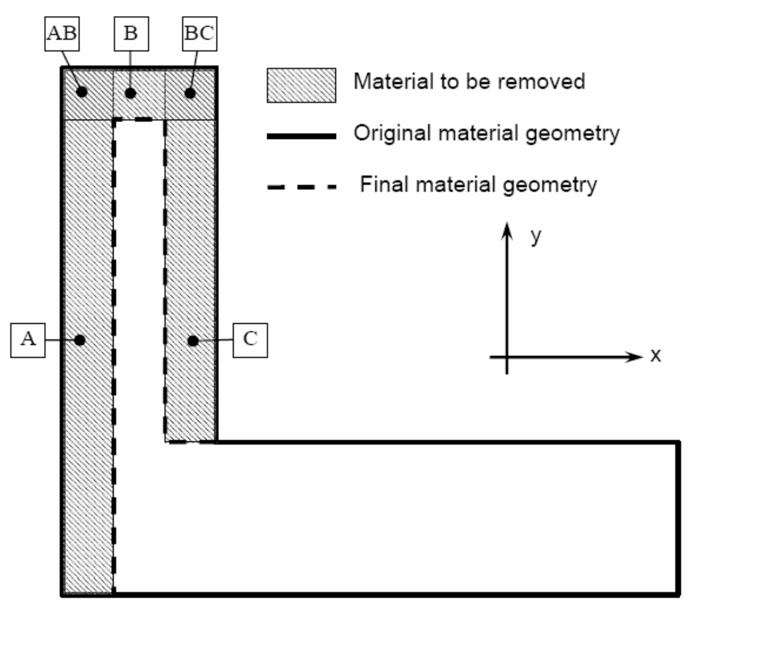


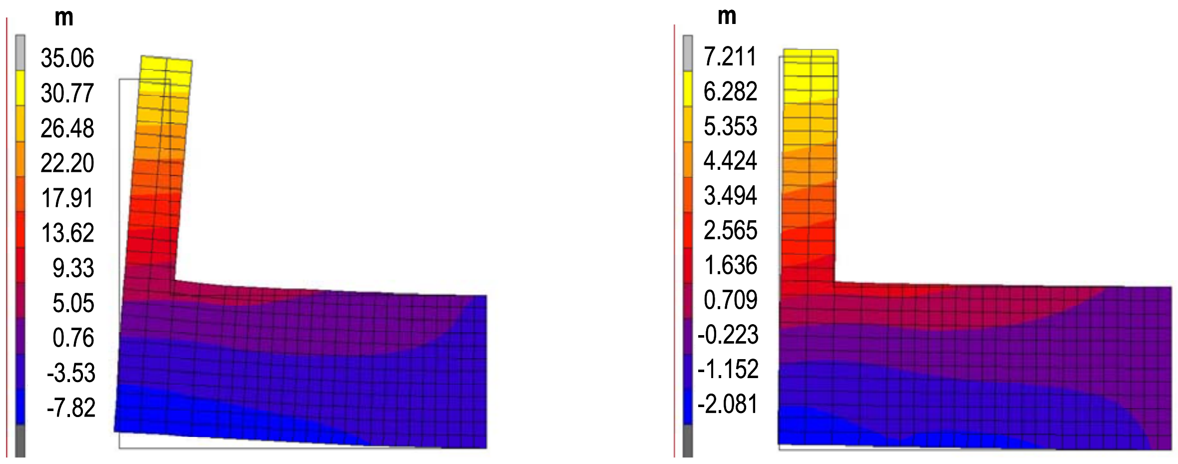
Figure 4: Material to be removed by machining.

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 after component being machined out of a forging (Distortion magnified 100x). Sequence 1 b) Final x-distortion after component being machined out of a casting (Distortion magnified 100x). Sequence 1.

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.

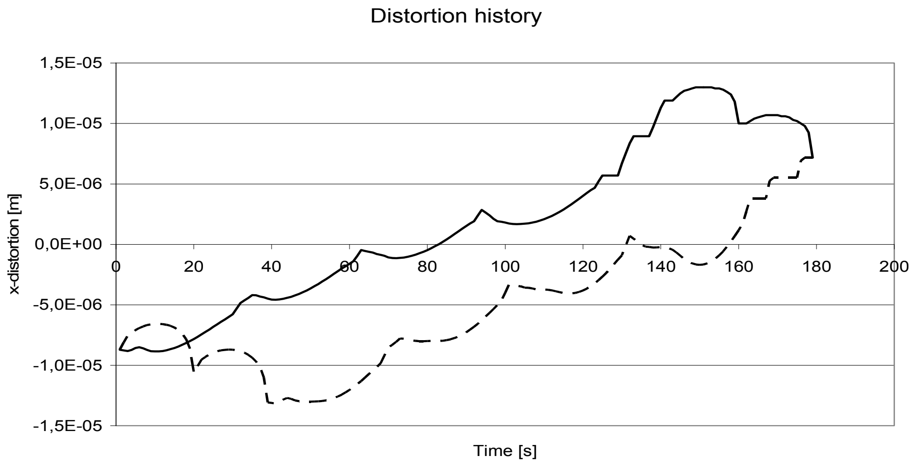


Figure 6: a) Distortion history in the case of machining in accordance with the sequences listed in table 1. The solid line represents machining sequence I, while the dotted represents sequence II. Shown is x-distortion [m] as a function of time [s] for the two cases.

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 early engineering design. 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.

Although the tool was developed for flange geometries generic aspects exists. The act of integrating a KBE system with a non-linear finite element solver is generic. Therefore this tool layout can be used for other product geometries with a slight detail modification of the scripts. In addition, the value of integrating simulation of other manufacturing processes, in a knowledge system as the one presented here, is believed to be great.

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

Design for manufacturing is enhanced by using the tool presented here since the influence of machining parameters such as machining order or cutting depth on component distortion can be determined by a concept designer 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. The tool also helps in bridging the gap between design engineers and computational experts when analyzing machining operations.

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