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Computational Support in Product Development

Applications from High Temperature Design and Development

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Division of Computer Aided Design

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by

Ola Isaksson

Akademisk avhandling

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Preface

This research has been carried out at the Division of Computer Aided Design at Luleå university of technology in close co-operation with Volvo Aero Corporation (VAC) in Trollhättan, which has been my daily work environment. I feel fortunate to be a part of such a co-operation that has proven that geographical distance does not matter if a spirit of possibilities, inspiration and belief is present.

I have become indebted to a number of people over the years since the start and no one is forgotten although just a few can be mentioned here.

Most important has been the always-present support from my supervisor, Professor Bengt-Olof Elfström at Volvo Aero. He provided me with inspiration, perspective and numerous of inspiring iterative discussions throughout the work. I am also most grateful to Professor Lennart Karlsson at the Division of Computer Aided Design who has initiated, facilitated and also co-supervised the work.

Many thanks also to all my friends and colleagues at Luleå university, at Volvo Aero and within the ENDREA[1] national graduate programme. You have all provided me with all the support I could ever ask for.

I've also been fortunate to co-operate with a large number of highly skilled people, among them my co-authors of the appended papers in this thesis who are (in alphabetic order): Professor Bengt-Olof Elfström, Peter Eliasson, Professor Steven Eppinger, Göran Fernström, Dr Peter Jeppsson, Dr Niklas Järvstråt, Professor Lennart Karlsson, Kåre Lodeby, Henrik Runnemalm and Sven Keski Seppälä.

Inspiring discussions with Dr Paul Couchman (University of Wollongong, Australia) on the human issues on product development and guidance from the Scientific Committee within ENDREA, especially Professor Krause (Techniche universität Berlin) have affected my work in a most positive way.

Financial support was initially provided by the Swedish board for Industrial and Technical Development (NUTEK) through the INPRO programme, but the final two years were supported by the Swedish Strategic Foundation through the national program ENDREA.

Finally, my deepest thoughts to my dear wife Helena and my son Björn who have supported me in the not always straight forward process of conducting research studies.

Trollhättan in December 1998

Ola Isaksson

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[1] ENDREA - Engineering Design Research and Education Agenda

Abstract

In this thesis a new perspective of Computational Support in Product Development is presented. It is explained and discussed how computational simulations can be used to achieve shorter lead time and improve quality in the product development process. The approach proposed is to use a generic and process based sequential decomposition of computational simulation activities in a product development project. This methodology, called a Generic Computational Support Process (GCSP), seeks to ensure that the best methods and tools available are used in all stages of a project and that critical weaknesses can be identified and consciously improved. To develop and test the GCSP the data flow and methods are identified and tested on real cases, in different applications and for different methods. The approach and have been tested and implemented in industrial practices and cases. The thesis consists of a survey and seven appended papers, describing the background, development, formulation and application of the GCSP. Most applications presented are computational support using FEM and CFD on high temperature design and development for jet engine components.

Keywords

Generic process, FEM, life prediction, continuos improvement, aircraft engine

Thesis

This thesis comprises a survey and the following papers, which have been slightly reformatted from where originally published. The contents are unchanged.

Paper A

ISAKSSON, O., ELFSTRÖM, B.-O. *A Method to Analyze Requirements on Product Technology*, Proceedings of the Third International Symposium on Product Development in Engineering Education, 8-11 December, Halmstad, Sweden, 1996, pp35-44.

Paper B

ISAKSSON, O. ELIASSON, P., JEPPSSON, P. *Integration of Thermal - Structural Analysis in the Product Development Process*, Proceedings from the 30th ISATA conference, Florence, Italy, 1997, pp 157-164.

Paper C

ISAKSSON, O. *A Generic Methodology for Computational Support in Product Development*, Submitted for Publication.

Paper D

LODEBY, K., ISAKSSON, O., JÄRVSTRÅT, N. *A Method for Uncertainty Quantification in the Life Prediction of Gas Turbine Components,* Proceedings from Fatigue Design 1998, Espoo, Finland, 1998, pp 39-48 (To appear in Specialist publication).

Paper E

ELIASSON, P., ISAKSSON, O., FERNSTRÖM, G., JEPPSSON, P. *An Integrated Design Evaluation System Supporting Thermal-Structural Iterations* , Concurrent Engineering: Research and Applications, vol 6, september, 1998 pp 179-206.

Paper F

ISAKSSON, O., KESKI-SEPPÄLÄ, S., EPPINGER, S. D., *Evaluation of Design Process Alternatives using Signal Flow Graphs*, Submitted for publication.

Paper G

ISAKSSON, O. RUNNEMALM, H., *Computationally Supported Assessment of Welding Distortions,* To be published.

Contents

1 Introduction

The cost of products and the lead time to develop these products are the two perhaps most important factors driving development of products in industry today. In addition, functional requirements and customer expectations must be met and failures to deliver so can be directly fatal for the success of the company. Product quality is becoming less of a competitive factor, and more of a pre requirement to operate in a competitive market environment.

The competitive situation has increased the motivation for companies to ensure that their capability to profitably develop and sell products is maintained and preferably increased compared with competitors. Continuos development of processes, practices and methods within this wide area of knowledge is therefore vital for surviving in a more global and competitive environment. The possibilities that arise from the rapidly developing area of Computer Aided Design [45,63] change the best practice of how to develop products.

This thesis treats one area of computer assisted technology that has a strong influence on design and development, namely the use of computational techniques to support product development. The work leading to this thesis has to a large extent been performed at Volvo Aero Corporation (VAC), a Swedish aerospace company doing business in all phases of the aircraft engine life cycle. The aerospace industry is known to intensively involve computational techniques in development [49], perhaps more than any other industry. VAC is a good example of a company in a business where skilful use of computational tools is an advantage. Some explanations to the importance of computational support in product development in the aerospace industry are given in table I.

Table I: Issues motivating use of computational support in aerospace product development

Issue	Comment
Expensive and time consuming testing	Motivates (reduced cost and lead time) use of alternatives and complements to hardware testing
Low weight designs	Requirements are high to extreme (in space applications). Optimised design solutions are often well worth the development cost.
High reliability requirements	All situations and aspects must be taken into account. Authorities strictly regulate qualification and verification.
High degree of complexity	Simulations and testing are continuously needed.
Life Cycle Cost (LCC) requirements	The Life Cycle Cost (LCC) measure requires the expected life of the product to be predicted during development.

In addition, most examples here are from high temperature applications of mechanical components where loads and materials are complex to model and describe.

Although applied on high temperature design, the methodology presented in this work is generic, and should be applicable to most industries where computational techniques are used in design and development.

The increased use of computational techniques in design has two principal explanations, namely;

CAPABILITY: Computational simulations provide the capability to derive quantitative information, that can be used to evaluate concepts, optimise product parameters, predict the behaviour of the forthcoming product (e.g. prediction of expected life) and more. This is a pre requirement for virtual prototyping.

MATURITY: Over the years CAD, Computer Aided Design, has matured from being an 'electronic drawing board' to an essential design tool [80], which includes support for manufacturing, simulations, drawings, illustrations and engineering management. CAD and CAE are cornerstones for emerging Knowledge Based Systems, KBE [17,29, 68].

Achieving an efficient use of computational support in product development requires development of a computer integrated design system [3,36]; development of computationally supported design processes [61] and to continuously account for organisational and human aspects [13,22].

1.1 Product Development

Product development has been defined by Ulrich and Eppinger as *the set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product* [71]. In a company, product development is often described as a process, the product development process, PDP. The PDP is more or less unique to the company's situation.

Lead time for development has been and is the major driving force to obtain competitive advantage, predominantly for consumer markets (cars, electronics, computers). Lead time has also become increasingly important in contract based development (aerospace, power plants etc.) where customers mainly are professional organisations and companies. Best practice in product development has been conceptualised into methods such as Concurrent Engineering (CE), Integrated Product Development (IPD), Integrated Product and Process Development (IPPD) and others. CE principles are valid throughout the entire Life Cycle [22].

Effective product development requires co-ordination and communication of market efforts, design and production [4]. No single peak performance within these areas will succeed alone. Another essential feature of effective product development, is the degree of overlapping of activities [11,73,77]. Development activities should preferably be carried out in parallel rather than in a sequence. Overlapping of activities requires intense communication between functions and facilitates both downstream integration and feedback while simultaneously minimising the total lead time. Overlapping and cross-functional co-operation are essential cornerstones of the *integrated* approach in development, requiring clear and intense communication.

The integrated approach is based on a number of identified success factors that have to be cautiously and patiently implemented in the specific company. No clear definition of success factors exists, but observations made have identified a number of 'key features', presented in table II.

Table II: Key features in successful product development identified by Syon and Menon [67]

Item	Feature
1	Multi disciplinary teams
2	Cross-disciplinary communication and coordination
3	Quality management methods
4	Computer simulations of products and processes
5	Integration of databases, application tools and user interfaces
6	Education programs for employees at all levels
7	Attitude from employees of ownership toward processes
8	Commitment to continual improvement

Although it is important to measure and evaluate the proposed benefits of using the integrated approach, it is quite difficult. Fleicher et al. [22] highlight three major difficulties quantifying the benefits of CE, namely: *Confusing metrics*, *Project variety* and the fact that *Implementation varies* in different industries and companies.

Another way of improving product development is by understanding and modifying the development process. The process is modelled and simulated in order to minimise lead time, maximise resource utilisation etc. Examples are found in [2,21,33,41].

Finally, during the late 80^{th} and early 90^{th}, management researchers found that a higher degree of overlapping of development activities in Japanese companies compared to western companies in the automobile industry could explain the advantage for Japanese companies [11]. Western companies have improved significantly since then and the difference is no longer apparent. To continue to increase competitiveness by reducing lead time in product development other techniques have to be developed. One such technique, called *front loading* by Thomke and Fujimoto [69], emphasises a more efficient problem solving methodology. Shorter lead time provided by virtual prototyping and computer simulations, rather than physical prototyping and testing, is in focus.

The possibilities to reduce lead time using computer aided design, modelling and simulation have now been recognised as some of the most important means to further improve product development [14,69].

1.2 Engineering design

Engineering Design (ED) deals with the theory and practice of designing products, involving basically the iterations between generating solutions (synthesis) and analysing them (analysis). In this thesis, ED is seen as a subset of IPD, and the relation between ED and IPD is given in table III.

Table III: Integrated Product Development vs. Engineering Design

Integrated Product Development (IPD)		Engineering design (ED)
IPD includes ED as one activity	↔	ED is a part of product development
Well known terminology in industry	↔	Mainly an 'academic' term
Emphasises a total approach (organisation, communication etc)	↔	Can be deployed by an individual designer
Clear definition and theory absent	↔	Theoretical foundations exists
Interpreted ideas and company specific processes	↔	General guidelines and methods

The iterative design process (find - evaluate) is widely accepted as fundamental in design e.g. [62, 55,78]. It is often described as a "Design-Build-Test-Analyse" process. One challenge is to combine the generative and creative part of design with the analytical counterpart - in design methods as well as with computer tools.

One approach to ED is to see design as a problem solving cycle, as the Basic Design Cycle by Roosenburg and Eekels [55] (also shown in figure 1). A second approach is to describe design as reducing the level of abstraction throughout the work [42,53,64,65]. A third approach is to view design as a phase model of product development [70,71]. An example of a phase model is represented by a concept design phase from Ullman [70] is shown to the right in figure 1.

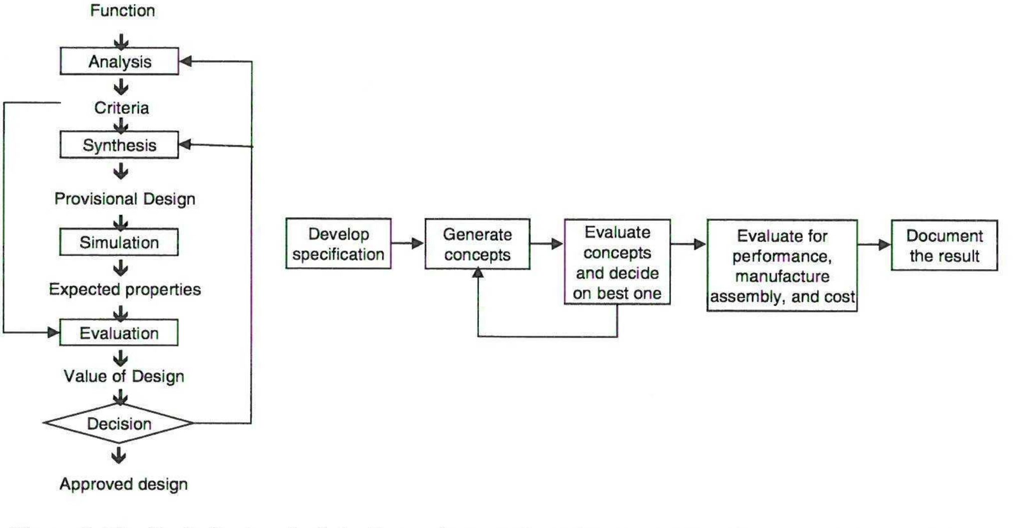

Figure 1: The Basic Design Cycle by Roosenburg et al. (1995) to the left and a concept design phase to the right by Ullman (1997).

These processes have no time scale, and can be applied in many situations. In this sense these methods are generic. Moore [46] points out that generic models are needed to improve the product development process. Still, for a specific problem in practice, the level of abstraction is often too high and the methods must be put into a context to be used effectively. How to apply these processes differs significantly depending on the situation. The project situation (time, resources, etc.), the kind of the design problem along with accessible tools and product data are some of the factors affecting how the process can be interpreted and applied in a specific situation.

Another aspect is that most design methods in the literature focus on the use of qualitative techniques for design evaluation, e.g. [53]. Generic computer supported design tools have recently been developed [1] based on these methods supporting qualitative evaluation. However, these tools do not include computational support. The need for quantitative analysis and evaluation methods in early stages of design has been identified as a research issue [24]. Computational simulations provide this possibility, e.g. [35], but geometric modelling have until lately been too cumbersome for regular use in early stages. Modelling and simulation in early stages have instead developed in the area of systems engineering [8,48,50] where no geometric models are used.

1.3 Computational simulations

In this work, computational methods are broadly defined as the methods used to find approximate solutions to mathematically described models of real systems. A useful definition by Neelamkavil [47] of a model is:

A model is a simplified representation of a system (or process or theory) intended to enhance our ability to understand, predict, and possibly control the behaviour of the system.

Here, the real system typically describes a geometrical domain (like a mechanical component or a fluid volume) while the system behaviour is described by partial differential equations, governing equations. For such models, computational methods can be used for simulation, where *simulation is defined as the execution of the model.*

Some popular computational methods are the Finite Element Method (FEM), see e.g. [7,12] and the Finite Volume Method commonly used in Computational Fluid Dynamics (CFD), see e.g. [72]. These methods require a discrete representation of the geometrical domain (a mesh), and the governing equations requires boundary conditions and initial conditions (for non-steady problems) to be defined.

For FEM, fundamental theories and specialist applications emerged during the 50^{th} and 60^{th} [26], and during the 70^{th} and 80^{th} FE methods were further developed and implemented into Computer Aided Engineering (CAE) packages intended for design. Somewhat later, CFD tools followed on, and the number of industrial users has increased dramatically during the 90^{th} .

Computational methods and tools origin from a specialist area and there is still a challenge to integrate these methods and tools into design and development theory and practice [9,24,55].

Currently, development of structural computational methods is to a large extent focused on technical issues like adaptive methods, more efficient numerical solvers and formulations, extended validity for non-linear problems and coupled field solvers. Another interesting development is to benefit from the progress made in the area of computer and database technology [51].

Computational methods can be applied to a large range of application areas [23]. In this work computational tools are used to predict the thermal and stress/strain behaviour in engine components, either during service or during manufacturing. To some extent, CFD applications for fluid flow simulation are discussed as well.

Generally, idealisations and uncertainties are introduced in each step of the process to reduce the physical behaviour of a system to solvable equations [5,43,77]. As an example; to define a discrete model for FE analysis of a gas turbine guide vane significant idealisations due to geometric complexity need to be made.

From a design point of view, lead time and validity for the entire simulation process are of vital interest. Therefore computer integrated design systems, which integrate computational tools, are developed [e.g. 20,31,32,35]. Pre- and post-processing issues are important, as well as methods to automatically assess accuracy of the simulations.

Computational methods can be implemented into computational tools with a varying degree of generality, as illustrated in table IV.

Table IV: Different levels of computational tools

Level	Explanation	Example
General purpose engineering systems	Typically includes geometric modelling, various simulation capabilities, drawing production, team work facilities and interfaces to production control systems.	IDEAS™ and ProEngineer™
General purpose computational tools	Limited functionality besides the implementation of the computational methods. These often have interfaces to complementary software, especially CAD for geometry models.	ANSYS™ and NASTRAN™ (FEM) and FLUENT™ (CFD).
Special purpose computational tools	Dedicated to special computational simulation applications. These tools are often proprietary to companies, and optimised for special types of designs. Better performance can be achieved to the cost of reduced generality.	Examples of commercial tools are Pam-Stamp™ (Sheet metal forming with FEM) and Fire™ (Combustion analysis with CFD).

Attempts and initiatives have been made to develop computational support systems for product development [10] which have focused mainly on the computer systems. Such approaches have been criticised for not taking human issues into account [40], and have frequently run into problems when implementing in the organisation [75]. Computational technologies have matured, and likeliness of successful implementations has increased.

Finally, since communication is one of the most essential aspects for effective product development, the exchange of computational information is critical. Within the STEP/EXPRESS framework [34, 52, 59] there already exist examples of successful utilisation of the standard regarding engineering analysis [31].

1.4 Jet engine technology

A brief introduction to how jet engines work will be helpful in understanding the product situation from which the majority of the examples are taken in this work. A good reference to gas turbine principles and design is found in [44].

A gas turbine engine uses a thermodynamic cycle, the so-called Bryton cycle, which consists of two constant pressure processes interspersed with two constant-antropy cycles.

This thermodynamic cycle is embodied in a gas turbine by a number of stages, see figure 2. In the fan and compressor stages, air is compressed. In the subsequent combustor stage, fuel is injected and mixed with the compressed air. The mixture is ignited and the resulting volume expansion is allowed only in the direction through the turbine. In the turbine, a part of the energy content is used for powering the fan and compressor stages. The remaining power is used for jet propulsion. In engines for transonic propulsion, auxiliary power can be generated in an afterburner.

For pure jet engine propulsion, all the thrust comes from the *core flow* passing through the gas generator (compressor - combustor - turbine). In most modern aircraft engines however, a part of the air that comes in through the inlet is 'by-passed'. This air is used for cooling in high temperature sections, and directly for propulsion. These engines are called turbofan engines.

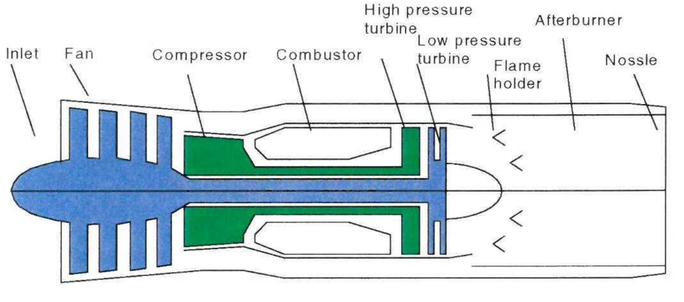

Figure 2: Principe of a low by-pass jet engine (turbofan) with an afterburner.

For air-breathing engines, the by-pass ratio tells us the mass ratio between air passing through the fan and the air going through the turbine.

$$BPR = M_{fan}/M_{compressor}$$

Generally, a lower by-pass ratio enables higher thrust to weight ratio and better high speed performance but also comes with higher fuel consumption. Hence, commercial turbofans have a higher by-pass ratio than military fighter plane engines. Raising the thrust to weight ratio also leads to higher temperatures and narrower design margins. The economical life of an engine is a compromise between these factors, which results in different engines for different applications. This is illustrated in table V.

Table V: Properties of different engines

Type of engine	Relative fuel consumption	Thrust/weight ratio	Economical life
Stationary gas turbine	1	1	200 000 hours
Commercial jet engine	2	5	40 000 hours
Military jet engine	5	10	3000 hours
Aerospace engine[1]	100	100	1 hour

For extreme applications such as rockets and aerospace engines the thrust to weight ratio is even higher. Instead of air, pure hydrogen-oxygen mixtures or solid fuels carried onboard are being used for combustion.

1.5 High temperature design

The development trend is to continue improving efficiency and performance (thrust/weight ratio) to an increasingly lower cost with increased reliability. Other requirements that have a big impact on development are environmental issues (emissions and noise), maintainability and manoeuvrability (for military engines). Lately, technology push have been replaced by technology pull [79], i.e. market requirements drive development rather than inventions in technology trying to find commercial applications.

Improving propulsive efficiency and performance can be achieved if the components can sustain higher gas temperatures. Different approaches are given in table VI.

Table VI High temperature design approaches

Approach to sustain higher gas temperatures	Consequence[2]	Comment
Allow higher material temperatures	Develop high temperature materials and material systems [19]	Materials capability has increased 120 °C in 30 years [16]. This increase does not require losses such as extra cooling.
Maintain material temperatures	Develop more effective cooling [18]	Cooling techniques have allowed 500°C increase in gas temperature over the last 30 years [16].
Reduce total load on components	Improve design methods [46]	Coupled aero-thermal and mechanical design emerging. Also design methods for using advanced materials and cooling technology are needed.

[1] Not an air-breathing engine

[2] For all these approaches, improvement in manufacturing technology is needed in parallel with design.

Advanced cooling has lead to complex internal shapes, see figure 3. Materials development challenges manufacturing and design techniques by introducing materials with anisotropic properties etc. Design methods capable of effectively taking advantage of new materials, cooling technology and aerodynamic coupling are thus needed.

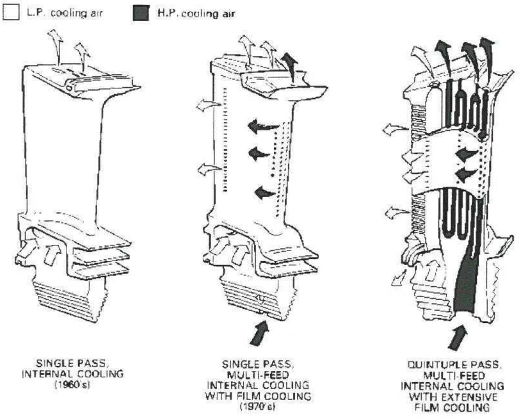

Figure 3: Advanced cooling has lead to complex internal shapes. (Courtesy of Rolls Royce [54]).

In table VII, a number of computational design issues are presented and how they can be approached.

Table VII: Examples of computational design issues for high temperature design

What	How	Examples and comments
Coupled field analysis	Integrated analysis	Heat transfer analysis, Flutter analysis, Acoustics by integrated fluid-structure computations
Life prediction methods	Improved computational methods	Material models, Load descriptions, Uncertainty quantification methods, Combined empirical-analytical methods, Validity
Computational support for the entire life cycle	Analysis of more aspects	Manufacturing simulation, Concept evaluation simulation, Detail Design simulation, Product support simulation
Traceable	Information modelling	Traceable simulation models, Coupling to PDM (Product Data Management) systems, Data storage, Reuse of models

1.6 Life assessment

Design requirements often include the life of the product. The predicted product life is the base for economical feasibility (LCC - Life Cycle Cost) and for maintenance planning. Life assessment techniques are therefore needed in all stages of a product life cycle. Life predictions are also needed for reliability assessment. Obviously, methods used to predict life differs significantly between the earliest assessments (where no geometry exist) and late stages where field experience and measurements may exist. The question remains the same, but the data and methods used are quite different.

Life prediction methods for aircraft engine components are based on the stress/strain history that combined with the temperature history causes fatigue, creep and other degradation phenomena. Computational simulations using FEM are commonly used to predict temperatures and stresses. Knowing the mechanical strain/stress loads there are several different approaches that can be used separately or combined [28,60]. Some of these are listed in table VIII.

Table VIII: Approaches to mechanically based life prediction, see also [6,66,74,76]

Approach	Explanation	Comment
Stress based approach	Damage models based on the stress range cycle. Used where $\Delta\varepsilon$ plastic=0. This is a quick and commonly used method for non-temperature dependent problems, experiencing HCF (High Cycle Fatigue). It is also a simple and quick method. Difficulties to predict short life (plastic strain) and variable load histories are severe drawbacks. These methods are not commonly used in aerospace industry. See also[6].	Simple method but not appropriate in aircraft engine applications, where $\Delta\varepsilon > \Delta\varepsilon_{elastic}$ and most problems are temperature dependent.
Strain based approach	Used where plasticity is involved in every cycle (LCF). Better prediction for temperature dependent problems, since these are often strain controlled in character. Methods exist to account for transients, temperature dependence, variable load and residual stresses. Still, these methods cannot predict propagation of cracks, which often makes a significant part of the time to failure. See also [6,26].	Can be used for temperature dependent problems [26], but is not appropriate for highly an-isotropic materials. Only crack initiation is possible to study.
Fracture mechanics approach	Most promising approach, in terms of accuracy. Assumes existence of an initial damage (defect). The disadvantages are the difficulties to simulate entire geometry's. Crack growth in the short crack regime is most important for critical aircraft engine components, but Linear Elastic Fracture Mechanics is not valid for the short crack regime, see e.g. [57,66].	Damage tolerance approach [12b,21]. Used for failure critical components in aircraft engines.
Cumulative damage approaches	Damage mechanics (e.g. [38]) and integration of time dependent phenomena (oxidation, creep, corrosion) [28,37,76].	Creep is often a concern for high temperature applications.

Fundamental for design of a product with respect to product life is to understand and carefully describe the load situation and use models that can describe the corresponding material damage mechanisms. Often, the load situation is complex, involving several more or less separable effects. Correspondingly, several different damage mechanisms contribute to the degradation of the product.

The best theories explaining fatigue phenomena are often phenomenological in nature (descriptive). Explanations to crack initiation (and propagation) are found on a small length scale, on sub grain size, or even on atomic level where the material cannot be described as a continua. Since structural life prediction models used in prediction (numerical prescriptive methods) most often assumes a continuum; these models are often difficult do combine. In other words, loads causing fatigue and creep are determined on component size level, and damage mechanisms are determined on a micro structural level.

It is as important as difficult to accurately predict the life of a jet engine component. There are many sources of possible errors, including accuracy of description of the load history, scatter in material data and reliability of damage models. Design methods taking the statistical variation into account exists, see e.g. [56,57]. The reliability of fatigue design methods is increased by systematic feedback from service.

Other aspects worth mentioning are the cost for materials testing. Once design experience and data exists for one class of materials, these are often chosen in favour of more promising materials (e.g. CMC's, TiAl's, etc).

Also, where several damage mechanisms occur simultaneously the summation of these are difficult to assess accurately. Often, the linear Palmgren-Miner cumulative rule for damage propagation is used.

2 Problem formulation

2.1 Observations

MANAGEMENT VS. COMPUTATIONAL METHODS: The development of computational techniques has (historically) been focused on modelling physical phenomena. To the extent that these methods have been introduced in industry, they have been used by specialists who are seldom tightly coupled to the core design team. Product development issues, on the other hand, have mainly been studied by management oriented researchers, where business and organisational issues are in focus. Interaction between these two areas of science has not been frequent, possibly since both terminology and research methodology are quite different. As the computational techniques have become more stable, powerful, implemented in Computer Aided Engineering (CAE) tools and most important, routinely used in design work there now exists a strong motivation to study the effect on product development by computational techniques.

ENGINEERING DESIGN VS. COMPUTATIONAL METHODS: Neither have the areas of design science or engineering design emphasised the role of computational tools and techniques, where other areas have been emphasised (e.g. Product structuring, Design for X etc.). Even in industry, computational work is carried out mainly by specialists and not by designers. In the aerospace area, specialists are becoming more directly involved in design and development while designers are doing more computational work themselves. The area of Knowledge Based Engineering (KBE) is emerging, where there exist a natural coupling between all areas of product development, such as simulation, design, production, marketing, acquisition etc. Product structuring and design methodology are needed to take full advantage of computational capabilities. Consequently, there exists a strong motivation for understanding how to effectively use computational techniques in engineering design

CROSS-DISCIPLINARY COMMUNICATION: Cross-disciplinary research, as well as cross-disciplinary work in PD teams, requires that traditional borders must be crossed. Computational specialists must anticipate ideas from management and design; designers must understand advantages and limitations with computational tools and managers must face new situations and develop new competencies. Communication means and a common taxonomy are needed to bring together these areas.

EFFICIENT USE OF METHODS: Computational methods are frequently used in industry today but surprisingly little attention is paid to evaluation of which method to use in different situations. Finding the critical path in computational support processes is essential both when choosing the best method for a design situation, and when identifying technology areas to improve. Poor use of computational support may even prolong the lead time and reduce quality.

2.2 Research question

A research question can now be formulated, based on the observations above:

> How can the use of computational methods be developed and managed to improve efficiency in Product Development (PD) in terms of lead-time and quality; and how can this potential be realised?

Answering this research question is expected to have the following impact;

IN INDUSTRY: An enhanced understanding for computational support within the product development organisation will enable better project planning and improve co-operation among all project members. It will facilitate the use of the most appropriate tool and technique in all stages of product development.

IN ACADEMIA: The results will contribute to a common platform for research relating to computational methods. Computational research will benefit as the impact on an industrial environment can be recognised. Management oriented research will benefit since the area of computational methods can be aggregated and its impact on product development studied. Research in engineering design methods can interpret computational methods in a design cycle context.

A research approach needs to relate to several traditionally different areas:

- Engineering design methodology and science
- Computational methods and techniques
- Product development and information management concepts

Also, a detailed understanding for computational support issues in product development is needed.

Such approach is different from existing theories and methods since development of computational support is studied from a product development perspective rather than on a computational method (and tools) level.

2.3 Research approach

On the basis of the introduction and problem formulation, a number of issues stated below motivates and explains the approach in this thesis.

PROCESS BASED APPROACH

Companies' primary goal is to be profitable through developing effective products (*design artefacts*) that satisfies customers. Products are developed by 'going through' the product development process.

Process development has the objective to improve the practice of developing products (*design processes*). This will result in a more effective company. These two perspectives are illustrated in figure 4.

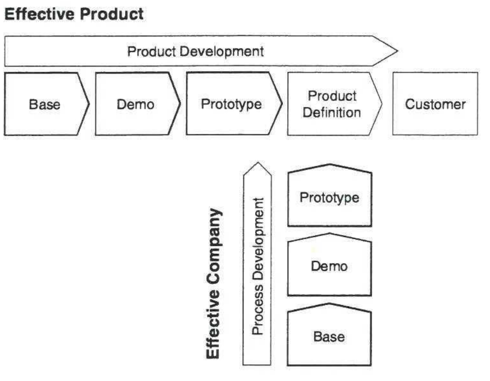

Figure 4: Process vs. Product Development.

Product development work is described in terms of processes. It is therefore also relevant to describe computational support in product development as a process.

GENERIC APPROACH

Computational methods used in product development are often described on a context dependent form. A methodology independent of the design situation and methods available is desired. To close the gap between management and specialists a *generic level* can be used (level 2 in figure 5).

MY APPROACH to answer the research question is to use a Generic Computational Support Process (GCSP) to improve efficiency of the computational support.

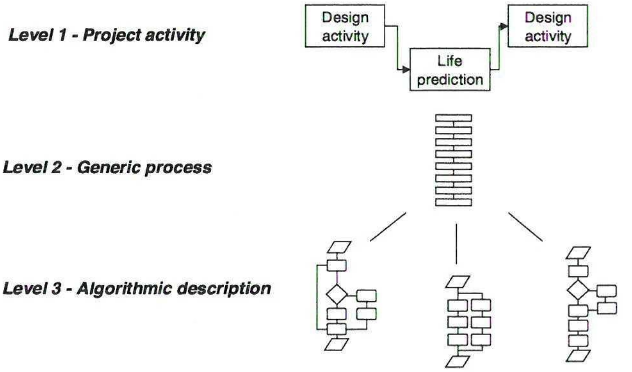

Figure 5: Generic level between management and operational levels.

Algorithmic methods (level 3) tend to be context dependent and difficult to generalise. Generic methods (level 2) are general and heuristic; i.e. they improve the likeliness of success. The advantage is that they can be used in a much wider (generic) context. Knowledge has to be shared within an organisation to gain competitive advantage [17]. The need for generic approaches in industry has also been identified by Chris Moore at Rolls Royce [46].

EXEMPLIFY ON INDUSTRIAL EXAMPLES

New design methods are often tested and exemplified on idealised cases. Difficulties, due to a greater complexity of the design problem, arise when these methods are implemented in industrial situations. To test validity and gain industrial feedback the method must be tested on real, or realistic, design problems. Different computational tools and situations have to be tested to assess validity of the generic approach.

PRESCRIPTIVE METHODS

Descriptive methods are useful for understanding, but prescriptive methods are the 'user mode' in development [30]. Much descriptive work has been done (and still needs to be done) but few of these concepts have been transformed into descriptive methods, suitable for industrial development situations. The objective in this thesis is to develop a prescriptive method based on descriptive knowledge.

MEASURES

Finally, it is important to evaluate the effect of using computational support on product development. The effect of introducing new methods and work processes should be possible to evaluate in quantitative terms, where especially lead time and quality are of interest.

3 A Generic Computational Support Process

In this section, a number of core steps for development and application of a Generic Computational Support Process, GCSP, are described. To a large extent, the method is described in paper C.

1. IDENTIFY THE DESIGN AREA

   First, an essential design area has to be identified where computational support is used. As an example, the area of life assessment of high temperature components in jet engines was identified as strategically important for VAC. See paper A.

2. IDENTIFY THE LOWEST GENERIC LEVEL OF ABSTRACTION

   Within the identified design area, several different computational strategies and methods may be used depending on the situation. To some extent, these strategies address the same issues where a sequnce of common and complementary steps have to be conducted for all different methods. The lowest (most detailed) level on which these common steps can be described is called the generic level. See also paper A, C, F and G.

3. SEPARATE SITUATION DEPENDENT FROM SITUATION INDEPENDENT INFORMATION

   The *activities* in a process are generic, i.e. they are *situation independent*. Each activity needs a *method* and *data*. Methods and data are *situation dependent* and the information therein cannot be formulated generically. The relation between a generic activity and its associated data and methods is described in figure 6.

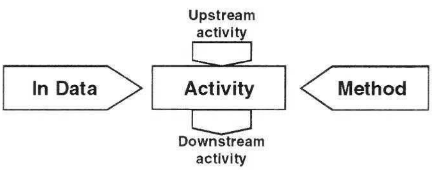

Figure 6: Generic representation of activity.

Activities are linked into processes, as shown in figure 7. As results are produced in one activity, these results are used (in combination with new data) in the downstream activity. See also paper C.

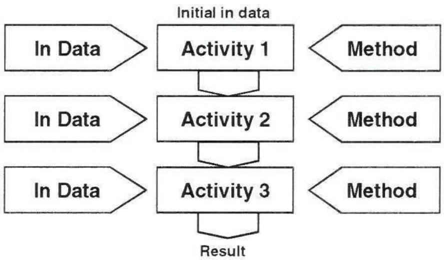

Figure 7: Generic process description of process.

4. THE GCSP

A Generic Computational Support Process, consisting of five generic steps accompanied by data and methods, is shown in figure 8.

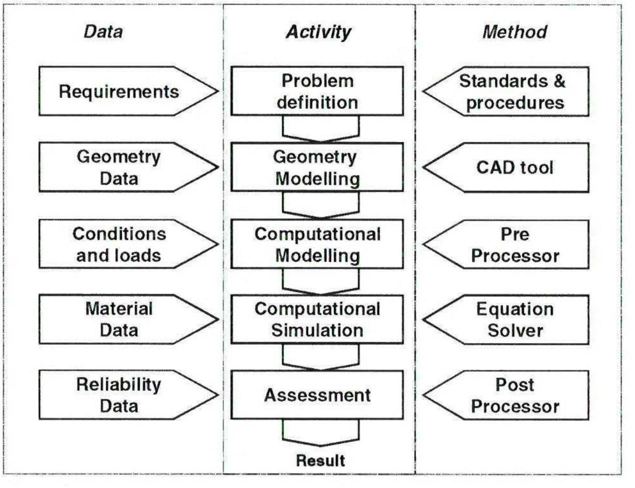

Figure 8: A Generic Computational Support Process, GCSP.

This process is basically a generic problem solving cycle, adapted to suit most computational problems. In addition each activity step is associated with data and methods, which contains situation dependent information.

Applied onto the design area of life assessment of high temperature components the GCSP takes a more detailed form, see figure 9. See also paper C.

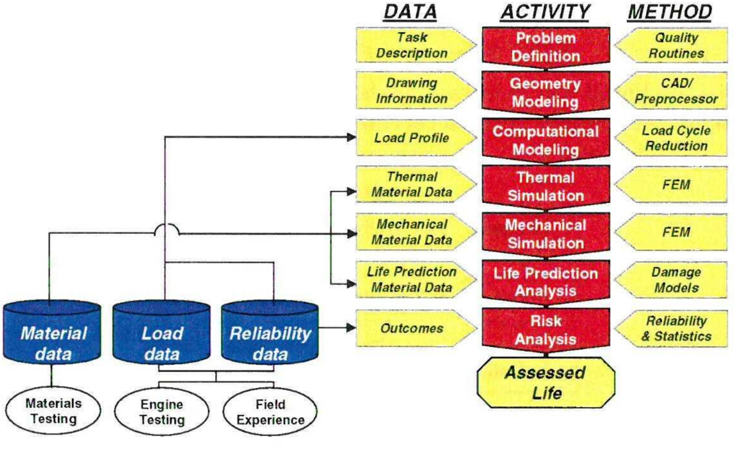

Figure 9: A GCSP for high temperature assessment.

This GCSP is valid for high temperature component life assessment and constitutes a base for further work. Further work may imply a computational iterative design system (e.g. paper E), uncertainty analysis (paper D) or methods development (paper G).

5. APPLY THE GCSP ON A SPECIFIC SITUATION

Implementation of the generic process in a specific situation results in an iterative and algorithmic description. This is the form used in most situations, but it has the disadvantage of being situation dependent. The advantages are that it can be implemented in a computer code, and repeated exactly. Lead times can be shortened drastically. However, the generic process description is better for discussions, identification of needs and weak links, competence development, quality systems and more, where a holistic view is beneficial.

The iterative nature of design appears, and sub-activities can be defined within the activities.

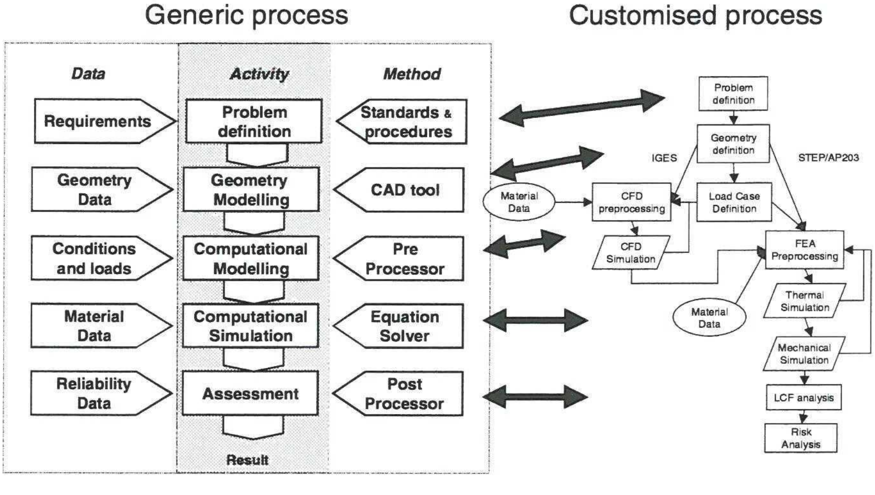

Figure 10: An algorithmic process in the generic process.

This is the level where the GCSP is configured to describe the task. It may be to improve the system, or simply to describe the system and define a common terminology. See paper C, D, E and G.

6. PERFORM THE IDENTIFIED SYSTEM IMPROVEMENTS

At this level, the tasks identified and described under the previous step (step 5) are executed. This task may be to improve a weak link in the computer design system in order to gain the proposed advantages. See paper B, D, E and G.

7. EVALUATE THE EFFECT OF THE IMPROVEMENTS ON PRODUCT DEVELOPMENT

Evaluation of the effect of improvements is important. For improvements in computer aided systems the effect is often drastically changed on a *local level*. As an example, translation of a certain class of data is possible after the systems improvement, compared to 'not possible' before the systems improvement effort. Lead time can in fact be cut from weeks to minutes. It is important but indeed difficult to evaluate the effect on a more *global level*, like the effect on the product development project. This is further discussed in paper F, where Signal Flow Graphs were used to simulate the development process, comparing alternative ways of deploying CFD in the development project.

4 Test and evaluation of the generic method

The GCSP methodology described in the previous chapters has been developed and tested throughout the research work. The results are explained and presented in the papers appended.

The generic approach has been tested at different abstraction levels and in different application areas such as life assessment, welding manufacturing simulation and iterative design. It has also been tested on separate jet engine components and automotive components, namely: a gas turbine guide vane, a flame holder, a combustion chamber, a turbine blade, a welded nossle and an exhaust manifold. Also, both FEM and CFD tools have been included in the examples.

In this way, the methodology has been tested on a wide variety of situations and with different objectives. It is argued that this method is generic and possible to use in different applications areas.

Use of computational methods has been developed and managed in the company (VAC) by using the GCSP as a development platform for continuos learning. The methodology has been used to describe, understand and communicate the computational situation at all levels in the company.

Efficiency has been tested by simulating the effect of improvements on a product development project with respect to lead time and quality.

The realisation of the GCSP has been proven by the fact that the method is being used autonomously in the company and in academic institutions. It is being used primarily as a methodology for structuring and communication of computational issues among specialists and non-specialists.

5 Discussion of appended papers

The first three papers deal mainly with how the generic process was developed based on an identified need for technology improvement. The later papers are concerned with testing and validating the methodology and investigating the generality of the methodology. The interrelationship between the papers is illustrated in figure 11.

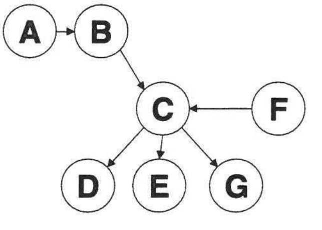

Figure 11: Logical coupling of appended papers.

The papers have the following interrelationship:

PAPER A: Identifying technologies for improving computational design methods.

PAPER B: Demonstration of one of the identified improvement areas from paper A.

PAPER C: Formulation and one application of the generic computational support process, GSCP.

PAPER D: Application of the GCSP on uncertainty analysis in life assessment.

PAPER E: Application of the GCSP on an iterative design process.

PAPER F: Investigation of the effect of introducing new technology on product development performance.

PAPER G: Test of the GCSP to improve computational support in manufacturing (welding).

There are seven papers appended in this thesis. On different hierarchical levels, they all represent different issues of computational support in product development. Their interrelation is illustrated in figure 12.

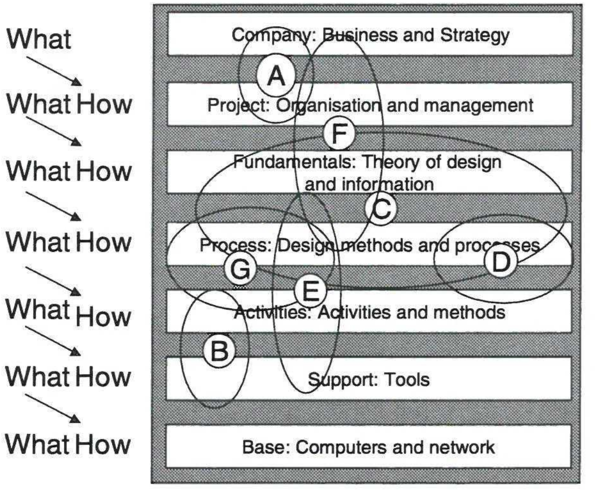

Figure 12: Levels of Product Development, illustrating computer aided support in development. The appended papers have been positioned in the figure (A-G).

Figure 12 illustrates different levels of detail, related to computational support in product development. The top level (Company) consists of strategic and business issues while the lowest level (Base) illustrates the computer hardware and infrastructure level. A higher level requires a lower level, and vice versa. The main focus in this work is on design methods (Process) and theory (Fundamentals) involving computational support. These levels immediately depend on the project situation (Project) and requires methods and tools (Activities and Support).

In the following pages, each paper is briefly summarised and discussed from this context.

PAPER A: A METHOD TO ANALYZE REQUIREMENTS ON PRODUCT TECHNOLOGY

AUTHORS: OLA ISAKSSON AND BENGT-OLOF ELFSTRÖM

SUMMARY

During product development planning, the need for forthcoming technology is assessed. In this paper a simplified QFD method has been used and described. In planning a product development project of an afterburner flameholder, high temperature design and particularly life assessment, had already been identified as a critical area for the future. The task here was to identify what technology improvements were needed in this area to meet the upcoming situation in the product development project. A number of essential technology improvement activities for high temperature life assessment were identified.

RELATION IN THESIS

Answers the question of how to identify critical technology activities to meet expected needs in product development. A structured approach to identify needs for technology support in product development process was tested.

One important observation was that complementary activities in an analysis chain should be analysed rather than comparing alternative technologies, see figure 13. This is the first observation, later leading to a generic process description.

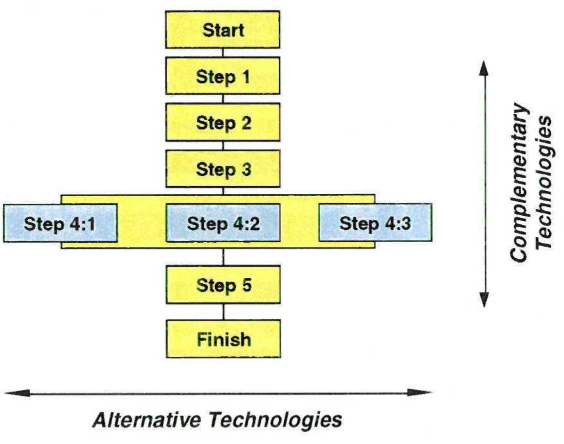

Figure13: Analyse and compare complementary technologies only.

RESULTS

The result was threefold:

1. A list of prioritised technology areas to improve. One of these improvement areas was later demonstrated in paper B.
2. The introduction of a structured approach to identify technology requirements in a group of different specialists was found to be quite useful as a communication tool.
3. Analysis should be done on sequential, complementary technologies rather than analysing alternative technologies.

PAPER B: INTEGRATED THERMAL - STRUCTURAL ANALYSIS IN THE PRODUCT DEVELOPMENT PROCESS

AUTHORS: OLA ISAKSSON, PETER ELIASSON, PETER JEPPSSON AND LENNART KARLSSON

SUMMARY

One of the identified technology areas identified in paper A was demonstrated in a product development project situation. Heat transfer parameters, calculated using CFD (Computational Fluid Dynamics) were used as boundary conditions on the structural model, and the technology improvement consisted in demonstrating this in a computer environment. The paper also discussed the use of solid models in a product development project at VAC.

RELATION IN THESIS

This demonstrated the development of a technology need, identified in the previous paper. Also, the paper contains observations on the use of solid models for gathering product information in a design team.

Using a common source for multiple purposes explicitly requires a common understanding among different specialists. This is a second observation, motivating a generic process description.

RESULTS

1. The proposed technology improvement step could be realised, and enabled the required design analysis. Lead time in transferring boundary values between CFD to FEM practically vanished. As a consequence, higher quality of boundary conditions could be used.
2. Also, using solid models in product development was found to be beneficial for communication within the team, which increased the focus. It was a reason to co-ordinate work and to manage concept versions. All had access to the same information.

PAPER C: A GENERIC METHODOLOGY FOR COMPUTATIONAL SUPPORT IN PRODUCT DEVELOPMENT

AUTHOR: OLA ISAKSSON

SUMMARY

Requirements on computational support differ during different stages of the product development phase. The requirements on how to conduct the computational support steam partly from the project situation and partly on the problem to be studied. In early stages of the development phase, little is known about the forthcoming product and the time for design iterations and analysis is short. As development work progresses, more information and details becomes clear and more efforts can be motivated and afforded for thorough analysis.

To clarify the role of computational support during such different product development situations a generic process description is proposed for computational support. This generic process can be used independent of the problem- or project-situation and is therefore a suitable platform for communication and methodology development. It is also suitable for analysis of the critical parameters for optimising further development work.

The generic process is described and exemplified on the area of computational life prediction of a jet engine, and worked through for a life prediction of a gas turbine guide vane.

RELATION IN THESIS

Describes the generic process methodology for computational support and illustrates the application of the generic process on life prediction of a gas turbine guide vane.

RESULTS

A generic computational support process, GCSP, where situation dependence and independence are clearly separated. This methodology can be used in different context as a means to improve efficiency and ensure quality of computational simulations.

PAPER D: A METHOD FOR UNCERTAINTY QUANTIFICATION IN THE LIFE PREDICTION OF GAS TURBINE COMPONENTS

AUTHORS: KÅRE LODEBY, OLA ISAKSSON AND NIKLAS JÄRVSTRÅT

SUMMARY

Uncertainties are introduced throughout the life prediction process. Instead of estimating the total error of the analysis in the end, errors were estimated for each of the generic activities in the life prediction process. Then the errors were summarised using gauss summation. Three examples were studied, on life predictions of different high temperature components. These three life assessments were different, both in that the components were different and that the project situation differed (amount of time and information available). By using the generic process description, these three analyses could be compared.

RELATION IN THESIS

Demonstrates one way of using the generic process to systematically address issues of uncertainty in life predictions.

RESULTS

One attempt to estimate (objectively) the uncertainty predictions that exist in a complex computational process. Relative (and absolute) errors are compared for three different life predictions. The method enabled comparison between different computational analyses (data and method) that addresses the same question.

PAPER E: AN INTEGRATED DESIGN EVALUATION SYSTEM SUPPORTING THERMAL-STRUCTURAL ITERATIONS

AUTHORS: PETER ELIASSON, OLA ISAKSSON, GÖRAN FERNSTRÖM AND PETER JEPPSSON

SUMMARY

A computer based design system providing multi-diciplinary simulation iterations was developed. The system supports the iteration between thermal fluid simulations in CFD and thermal structural simulations in FEM using two commercial simulation packages. In the design of high temperature components, the physical interaction between fluid and structure has often been neglected, or treated primitively in design stages in product development. One reason is the traditionally separate simulation environments for fluid and structure analysis, which has required special, multi-diciplinary packages. Improving this infrastructure enables simpler iterations, and the reduced lead times in iterations allows accounting for multi-diciplinary effects in design. The design system is illustrated on an example, an exhaust manifold, where the thermal interaction between fluid and structure is of great importance.

RELATION IN THESIS

Demonstrates the use of GCSP to develop and use an iterative design evaluation system. Systematically using computer integration enables multifunctional computational support in a design process.

RESULTS

Possible to automate the design process, and enable iterations for increased quality of the product. The computational support is consciously integrated with the iterative design process.

PAPER F: EVALUATING DESIGN PROCESS ALTERNATIVES USING SIGNAL FLOW GRAPHS

AUTHORS: OLA ISAKSSON, SVEN KESKI-SEPPÄLÄ AND STEVEN EPPINGER

SUMMARY

How do we know whether a change/altered development process really is worth while? Commonly, a company continuously spends significant efforts in developing their development processes, but on what basis are these introduced?

The introduction of new design activities into an established product development process may involve more work in the initial stages of development. Yet this extra effort may reduce the need for more expensive and time-consuming redesign activities later in the project. We have studied a case where more intensive use of computational simulations in the early design phase means that fewer hardware tests are needed because the designs can be analytically evaluated in advance of physical testing. Total development lead time and cost can thus be significantly reduced.

This paper addresses how to evaluate alternative design strategies and methods with respect to their impact on the development process time. This is achieved by analysing the design process using signal flow graphs. The technique has been applied to jet engine component development projects at Volvo Aero Corporation in Sweden.

We have found that evaluating alternative processes using signal flow graphs not only is helpful to assess the effect of introducing new or improved design activities on the development process, but it also facilitates the discussion of process improvement alternatives and tradeoffs for an organisation.

RELATION IN THESIS

This is an investigation of the effect of introducing new technology on product development performance. It is vital to evaluate the effect on product development projects using computational support. The effect of introducing new and improved methods has been evaluated in quantitative terms. The measure used was expected lead time to project completion. By presenting the simulation results as cumulative probability quality issues of the development process can be analysed. The generic process was implicitly used to define the simulation model on a suitable level of abstraction enabling comparison.

RESULTS

The effort spent on iterative hardware testing can be compared to cost of spending more (initial) efforts on computational simulations. Signal Flow Graphs was found to be valuable tools to assess the effect of alternative processes. However, the problem comes down to the quality of data. Probabilities are difficult, or even impossible, to assess strictly objective.

Increased reliability motivated CFD to be used directly as a lead time critical design activity. According to the simulation results, this approach can be motivated if the success probability of the PD project was to be higher than 80 %.

PAPER G: COMPUTATIONALLY SUPPORTED ASSESSMENT OF WELDING DISTORTIONS

AUTHORS: OLA ISAKSSON AND HENRIK RUNNEMALM

SUMMARY

The welding operation in manufacturing of thin walled pipe structures has been studied, using adaptive non-linear finite element techniques. This simulation technique is computationally costly, and only simplified models can be studied.

The GCSP is applied to the welding manufacturing simulation process and used as a platform for improvement. Iterative simulations of welding process parameters and mechanical restraints are made on elementary cases, and the simulated distortions presented in a Welding Response Matrix (WRM). Based on the most promising elementary case, two simulations were made with a more accurate description of geometry. The trend from the elementary case was compared with the results computed for the second set of simulations.

RELATION IN THESIS

The GCSP is used as a development platform to develop simplified approaches to using advanced manufacturing simulations to support analysis of manufacturing problems.

RESULTS

The results indicate that manufacturing processes can be analysed by iterative simulations of elementary cases. Behaviour of the elementary case with respect to boundary conditions and welding operation parameters can be optimised, since computational lead time can be kept short, and a larger model can be used to 'verify' the results from the elementary studies.

Also, using the GCSP as a structured development platform enabled communication between computational specialists and non-specialists.

6 Conclusions

Computational methods have become more integrated into design and development work, and have been recognised as a major possibility to shorten lead times in product development.

Quality assurance and continuos learning are two issues of importance for improving the use of computational support in design and development to reduce lead time and cost. Using a process oriented view, these issues can be addressed in a structured manner.

In this thesis it has been demonstrated how a generic computational support process, GCSP, has been used to improve effectiveness of computational support. The method provides a flexible way to describe, understand and communicate the computational situation. Major benefits of such an approach have been as a communication tool in the organisation, and as a platform for addressing relevant issues and exchange experience. Bottlenecks can be identified already in the planning stage and be systematically improved.

Identification of forthcoming technology improvement areas is one example of application and quantification of uncertainty sources another. This approach has also been demonstrated to be a suitable tool for quality assurance issues regarding simulation and computational activities.

In this thesis it has been show how the use of computational methods can be developed and managed to improve efficiency in Product Development in terms of lead-time and quality. The potential has been successfully demonstrated in a number of different applications and situations, both in industry and in academia.

7 Discussion and further work

The process based approach used in this work is a way to work with continuos improvement. As a process has been identified, lead times can be measured and the process can be changed. Information, methods and experiences can easier be exchanged within the organisation, as a common language is established.

At different stages of the development process, different information is available, and different methods are appropriate. The premises from a product development perspective on an accurate method, is how well it can be used to solve the task, see figure 14.

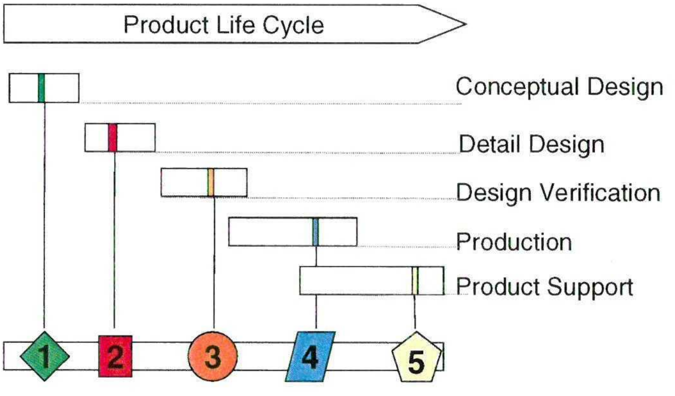

Figure 14: Different methods, answering the same question, under different stages of development.

Thus, mapping the features, properties and measures of methods in such figure, enables characterisations of methods. Requirements on accuracy of the methods used increase as the product goes through the development- (and life-) cycle. It is not necessarily that the lead time increases in proportion to the accuracy if the models can be re-used in downstream phases. In figure 15, each of the analyses made in the different stages in figure 14 are compared, in terms of their accuracy, flexibility, lead time and cost.

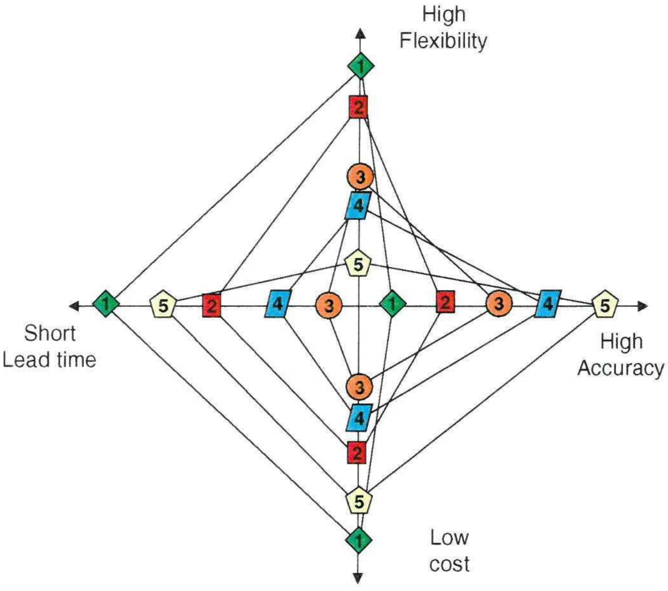

Figure 15: Profile of different methods.

The optimal method would have high values on all axes, but there is no such method. If a 'perfect' method exists there would be no need for other methods. By considering the simulation models in a life cycle perspective cost and lead time can be gained.

Information modelling and information maintenance are areas of immediate and future interest for computational simulation support in product development. Since generating models is time consuming, but updating these models are not, it is important to be able to re-use these models over many years. Also, collaborative development of products where many different partners are involved in the design work, requires that the models can be worked on simultaneously using different tools. The information infrastructure of design and simulation tools must be improved.

Also, computational simulation can be a support for both manufacturing, design and maintenance. Simulation technology is rapidly moving forward and can be seen as a mediator, in introducing new work procedures. In the integrated framework, the GCSP is one relevant methodology useful for reducing sub-optimisation, and improving communication between disciplines.

A number of areas for further work can be identified:

One possibility is to apply the generic methodology to more areas, measuring lead time and quality, as a way to systematically improve computational support processes.

Another possibility is to work on the methodology. This is interesting from an applied perspective, where the method requires training and experience for engineers and designers in development situations. It is also interesting from an academic perspective where validity and relation to established theories can be further investigated.

A third possibility is to develop the information infrastructure (integration between tools in computer integrated design systems). Interesting work is being made within the STEP framework. The STEP framework also provides a natural coupling to PDM (Product Data Management) systems which is needed to fully integrate computational support in industrial product development.

Finally, the presented work has presented a structured approach to systematically developing computational methods and tools which can also be used to consciously improving the entire development process.

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Paper A

A Method to Analyze Requirements
on Product Technology

Third International Symposium on Product Development in Engineering Education, Halmstad, 1996, pp 35-44

A Method to Analyze Requirements on Product Technology

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ABSTRACT A structured method for selection of technology requirements is described which exemplifies a concept for continuos development of organization, coworkers and methods. Using a process oriented view for product planning, needs for improved technologies have been identified at two business centers at Volvo Aero Corporation.

Structured analysis is introduced by using a simplified QFD analysis approach, illustrating the key principles of structured analysis. The objective of the analysis is to obtain overview of technology requirements and then define detailed technology programs. The examples discussed are on methods and technology for gas turbine high temperature components. The technology improvements are then continuously integrated with ongoing product development.

1. Introduction

At Volvo Aero Corporation in Trollhättan, extensive work on process planning has been carried out over the last four years (Loinder, 1996). This has led to a continuously maturing, process oriented, way of describing and planning work. This is considered to be one key factor in a learning organization and for a successful implementation of integrated product development (Wheelwright & Clark, 92, Harano & Johnson, 94). A research project for developing a life prediction analysis system in parallel with an integrated product development project was started as illustrated in figure 1. In this research project the technology development areas, identified using the structured analysis described, are in focus.

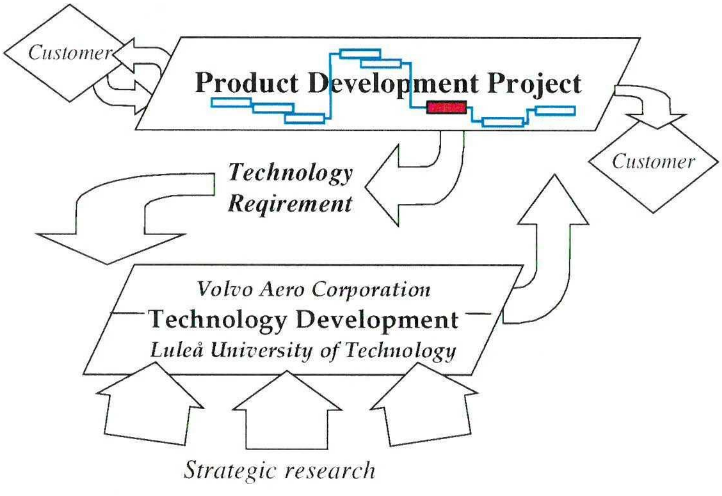

Fig 1: *Technology requirements identified in project planning initiates a research project, running in parallel with the product development project.*

If expected technology requirements are analysed in the planning stage of a product development program, the requirements can initiate appropriate development programs. It is assumed that low risk, incremental development, can be developed parallel and integrated with the product development project while high risk, strategically important, requirements must be used as input to the company technology plan (Roussel et al, 1991, Wagner, 1995). See figure 2. In this context, technology includes: methodology, analysis methods and information processing in design and analysis systems.

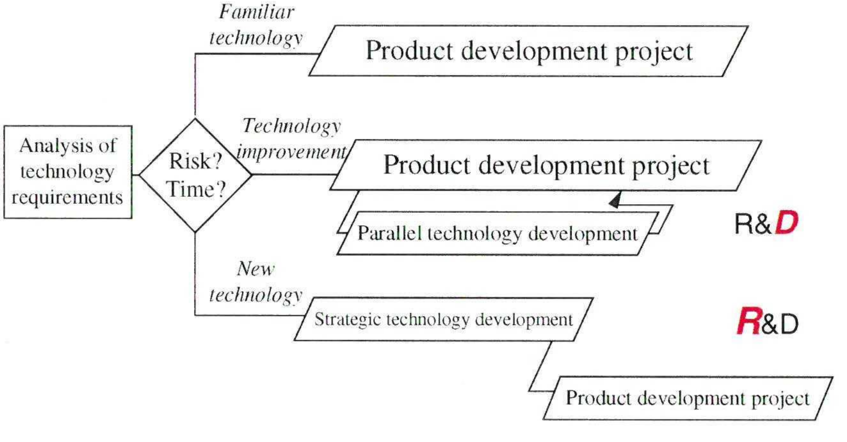

Fig 2 *Requirements from product development planning process initiates different technology development programs.*

The use of a process oriented view in project planning is vital for identification of requirements. Structured analysis is seen as the tool to identify requirements and relate them to development programs.

Currently, only the key principles in structural analysis will be used. Later, as this simplified method has been established and accepted in the organization, improved methods may be applied.

2. Theory and Findings

The needs identified in the product development planning process, are used as input to the technology requirements analysis. The structured analysis results in a relationship matrix which has to be carefully evaluated. The evaluation is used for technology development planning. This is described generally and exemplified below.

2.1 Structured analysis of requirements

Quality Function Deployment, QFD, is a method used to relate customer requirements to the parameters affecting them (Hauser et al, 1988). QFD can be also be used to decompose complex engineering processes while considering different aspects of the complex process (Maier, 1993).

Translating the 'What's' into 'How's' systematically, is a powerful way to gain an overview of the area. Here a limited form of QFD analysis, using only the relationship matrix (see figure 3) is suggested. This limited form of QFD analysis is a way to formalize and document the discussions what would be necessary. The resulting matrix, and the discussions between experts and strategists, results in a more solid base for technology planning.

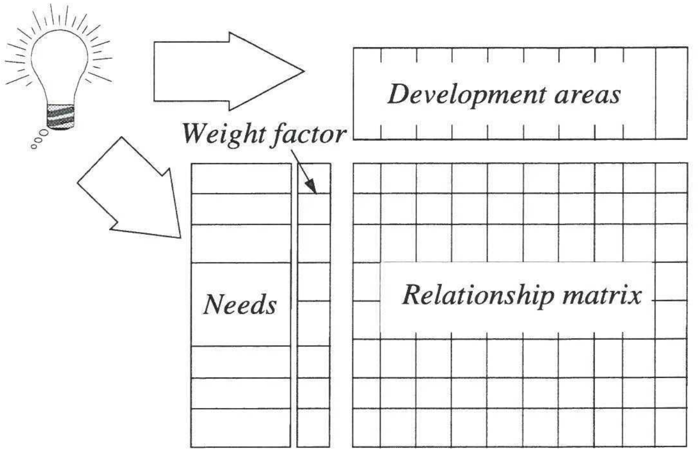

***Fig 3** Principle of relationship matrix, where weighted needs are related to technology development areas*

2.2 Analysis phase

A team consisting of five to seven experts are gathered, preferably representing the different disciplines involved in the area of analysis (Harano, 1994). Representation of different areas of knowledge contributes to a more objective view of the technology area. One, preferably technically unbiased, discussion leader with experience from structured analysis chairs the sessions.

The first meeting is short, with the intention of defining *aims* and *limitations* of the analysis. Activities before defining the detailed aims are;

- Introduce new participants to the method.
- Identify the customer in this context; who is going to use the result of the method analyzed and how is the result from the analysis going to be used?
- Is there anyone else who should attend, representing other aspects?
- Discuss, and agree upon, characteristic definitions such as '*What is meant by high temperature*?', '*What is included, and excluded, in the method studied?*'
- Finally, make clear the financial aspect and the time limitations for the analysis itself as well as the area to be studied.

As these aspects have been discussed it is time to formulate written aims of the structured analysis. One key person, responsible for the analysis, writes minutes of the meeting and prepares the next session.

The following meetings are to complete the relationship matrix following the steps described below;

1. Formulate requirements on technology

   The 'What's' are specified using a brainstorm technique (Rise et al, 1993). The participants writes down requirements on small stickers and places them on a wall. The requirements are formulated to fit into the question *'The method/technology shall be ______!.'*

2. Group the requirements

   The requirements are collectively grouped at the wall into five to ten groups, covering the needs. This is initially done under silence, and discussed afterwards. After the meeting the definition of these groups are described in a few sentences based on the original stickers and the discussion, and added to the minutes.

3. Weight the requirements

   Each requirement is judged on a scale from one to five, in order of increasing importance. Several requirements can have the same weight.

4. Identify the technology areas in the method

   If the method is described by a defined process, the individual activities of the process are used. If no defined process exists then the same brainstorm technique can be used to identify technology areas ('how's') affecting each requirement. This is done by finding technologies, responding to the statement *'This technical area affects the method'*.

5. Relate the requirements to the technology areas

   The correlation is performed by asking how big impact an *improvement* of each technology area has on each requirement. The correlation can be expressed using either numbers or symbols representing the strength of the relation. If numbers are used, caution have to be stressed since they are not absolute in any sense. Suggested numbers are 0, 1, 3 and 9 where 9 represents the strongest correlation and 0 represents no correlation. Negative effects can similarly represented by negative numbers.

2.3 Evaluation phase

The relationship matrix is only used for supporting the evaluation. Careful judgment and experience are most important and any deviations from expected results must be further investigated. Technical risk, financial limitations and expected development time determines the appropriate development form as illustrated in figure 2 (Roussel et al, 1991).

2.4 Examples from Volvo Aero

This technique has been used to identify the technology needs for improved high temperature component life prediction methods at the Military Engines Division. This area of technology had previously been identified as a strategically important technology area and the aim was to identify the requirements on high temperature life prediction technologies and relate them to possible developments areas.

A brainstorm resulted in a large number of requirements on life prediction methods which were grouped as described above. After the meeting, a description of each group was formulated. As an example the description of the requirement 'thorough' was

'A thorough method shall always be conservative (but not too conservative) and have a known accuracy within the known and defined region of interest. Furthermore it should be easy to verify'.

When discussing the definitions of technology activities it was useful to divide them into *complementary activities*, where the activities solves different tasks in the process, and *alternative methods*, when different methods can be used to solve the same task. When analyzing technology areas, it is important to only compare complementary technologies. Alternative technologies requires comparative analysis and tests which cannot generally be judged at a meeting, but can be suggested as a result of a structured analysis. This idea is shown in figure 4.

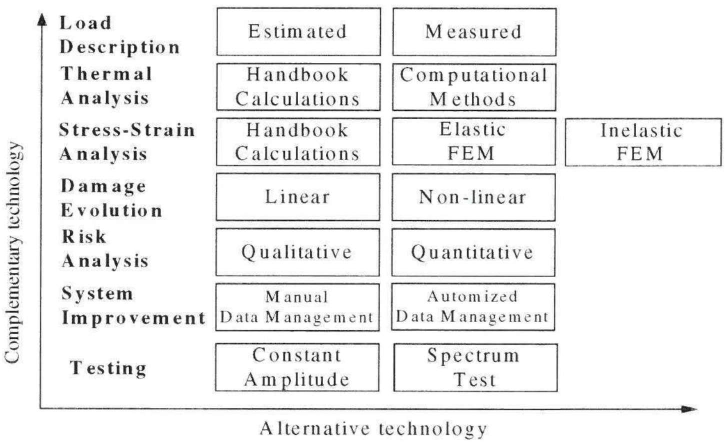

Fig 4 *Illustration of complementary vs. alternative technologies in an analysis process. For example, an improved load description is compared with an improved thermal analysis, without discussing whether estimation or measurements should be used.*

The relationship matrix was completed and the form used is illustrated in figure 5.

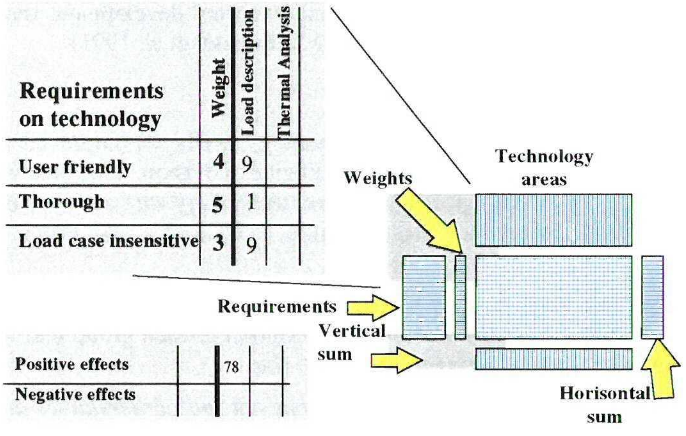

Fig 5 Relationship matrix

This technique has also been used as a step in identifying technology areas, important for realizing strategic product goals, and relate them to important technology areas at the Combustor Division. In both cases, the result formed the base for technology program planning using road maps (Barker & Smith, 1995).

When analyzing the result of the analysis, it was found that the most high impact technology improvement areas implied rather extensive development efforts. Typically these areas concerned the development of higher competence in crack propagation or extensive materials testing. However, some technology improvement areas where characterized as medium efficient in terms of expected impact on the life prediction methods while they were achievable in a low cost and low risk development program. One such area was to enable the integration of thermal boundary conditions, calculated in Computational Fluid Dynamics (CFD) simulations of the gas flow, to boundary conditions for structural Finite Element Analysis (FEA). Expected results were more accurate results due to more accurate heat transfer calculations and shorter lead times in data transfer from CFD to FEA engineering tools.

Improved performance of life prediction methods can be realized by developing either the analysis process or the detailed techniques forming the process. The optimum is to improve both the process and the techniques.

3. Conclusion and Recommendation

By introducing *only* the key principles of QFD analysis we successfully gained an understanding and acceptance for structured methodology. Further, it provided a forum for cross functional communication within the organization and a holistic view of life prediction analysis could be maintained. As these simple but fundamental ideas have been established more refined techniques can be introduced. In this way we established a learning methodology in the organization.

It was found that the structured analysis process ran much smoother if only complementary technologies were discussed during the meetings. Impact of alternative analysis cannot be judged at a meeting since these often requires comparative analysis. Comparative analysis can very well be an outcome of the structured analysis.

In the analysis at Volvo Aero, it was suggested that computer system improvement would be a low cost and low risk development effort. Integration of heat transfer results from computational fluid flow calculations to finite element structural analysis was suggested to be beneficial with respect to analysis lead time and accuracy in the life prediction. Since this is an *improvement* of technology, it can be developed and implemented in an ongoing product development project.

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Paper B

Integration of Thermal-Structural Analysis in the
Product Development Process

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Integration of Thermal - Structural Analysis in the Product Development Process

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ABSTRACT Trends of more team working and cross functional activities in Integrated Product Development increases the requirements on the computer aided engineering technology used.

Experience of using solid models in a product development project at Volvo Aero is presented. Further, it is described how thermal boundary conditions, calculated using Computational Fluid Dynamics simulations, can be integrated with thermal structural analysis in a commercial Finite Element code.

It is argued that incremental technology development using technology based on international standards, e.g. the STEP standard, is a low risk- highly efficient strategy for improving multi functional analysis systems.

1. Background and introduction

To be able to effectively compete in an intense and rapidly changing environment, development capability has become a key term in engineering management [1]. The question of how to develop new or improved products has been placed in focus, and is often described as a process, the product development process [2].

In this article, we discuss experience from Volvo Aero Corporation of working with a solid model based product description during product development. It is also discussed how thermal boundary conditions, calculated in Computational Fluid Dynamics (CFD) are used to describe the heat load in thermal and structural Finite Element (FE) simulations, by the integration of these tools.

1.1 Requirements in integrated product development

Terms like Concurrent Engineering (CE) or Integrated Product Development (IPD) are concepts for product development. These emphasises a number of issues, typically participation in early activities of downstream functions, parallel work etc. Conaway [3] describes IPD as a management strategy that uses customer inquiry, cross-functional teaming and technology integration to improve the performance of product development.

Effective communication, in various forms, is an important issue for realising these ideas. Information technology is seen as an enabling technology, providing communication in product development.

In the same spirit, Finger & Dixon [4] outlines a number of "outstanding research issues" in mechanical engineering design. One issue is analysis methods in early and intermediate stages of design. Methods are lacking for the evaluation of alternative concepts, and configurations. Another issue of importance mentioned is the design of a design environment that integrates available tools. Several different disciplines of traditional analysis is now often integrated in single design activities.

1.2 Integration of computer aided engineering tools

Integrated analysis requires well established communication between the computer aided engineering (CAE) tools involved. The integration of these tools can be worked out using direct interfaces or via common databases, preferably on a neutral format [5].

According to Park and Felippa [6], computational analysis of coupled field problems, such as fluid - structure interaction can be approached by either *integrating the interaction effects in an existing code*, or by partitioning the analysis and *providing communication capabilities to the different codes*. Advantages using the latter are twofold; the most appropriate single field analysers can be used and the modular way of implementation maintains flexibility. The requirements of an efficient and controllable interface between the codes increases though. This is especially true when using commercial software, where the access to the source code and the database format is limited.

1.3 Product information modelling using STEP

In order to exchange information between systems via a database using a neutral format, the format of the information in the database has to be agreed on.

One way is to find a standard that covers all the entities of interest and implement that standard. Two difficulties encountered in this approach are to find a standard that actually covers all the information that is, and will be needed, and also to interpret that standard. Many standards only define the data model for the information, and the interpretation rules for the model are typically implicit [7]. Since human interpretation is required in order to implement the standard, different persons may interpret the standard differently.

Another way is to define a format specific to that problem. For everything but a small project this is an extremely cumbersome process.

A third, and better, method is to use the most appropriate application protocol of the STEP (Standard for the Exchange of Product Model Data) standard, formally known as ISO 10303, for the problem. Application protocols, AP's, are information models developed for a particular application context, e.g. AP209 - *Composite and metallic structural analysis and related design* [8]. An information model provides not only the description of the data, but also an explicit set of interpretation rules for the data [7]. Implementation then becomes less dependent on human interpretation.

In the presented project we have chosen the latter approach, i.e. extending an existing application protocol of the STEP standard.

1.4 Implementation of new technology

Improving an engineering system step by step is called incremental research [9], since the development is based on established technologies. This does not imply as high technical risk as more fundamental research projects and time to benefit is shorter.

A structured method for analysing the requirements on life prediction technology for high temperature components was carried out at VAC [10]. It was suggested that improving communication between CFD and FEM would be a low cost and low risk development area with potential benefits in terms of reduced analysis lead time and improved accuracy of the analysis.

2. Solid modelling in product development at VAC

Volvo Aero Corporation (VAC) develops and produces gas turbines for civil and military industry as well as for the space industry, in collaboration with major aerospace companies. Due to the long operating life cycle of jet engines in aeroplanes, typically 30-40 years, these engines are continuously improved. Component development and introduction of new materials are motivated by customer requirements such as lowered life cycle cost and increased performance.

Solid models of jet engine components are being used in development projects at VAC. The time spent in creating and modifying these models can be gained as the completeness of the information in a solid model is superior to drawings. However, a requirement for efficient use is that the solid model can be used for other activities than just drawing production.

2.1 Product development process

At VAC, a process oriented view is used in planning and managing product development. 'Tollgates', are the activities where major decisions which separates the different stages in product development are made. Most activities in-between these tollgates aims at providing the information necessary for efficient decision making. Engineering analysis is often a vital part in achieving this information.

The requirements on engineering analysis used changes as the product development project matures. In early stages of the product development process, rapid modelling and comparative analysis are important issues for evaluation of concepts, whereas in later stages quantitative assessments and deeper investigations have different requirements on the engineering analysis tools. This is illustrated in figure 1.

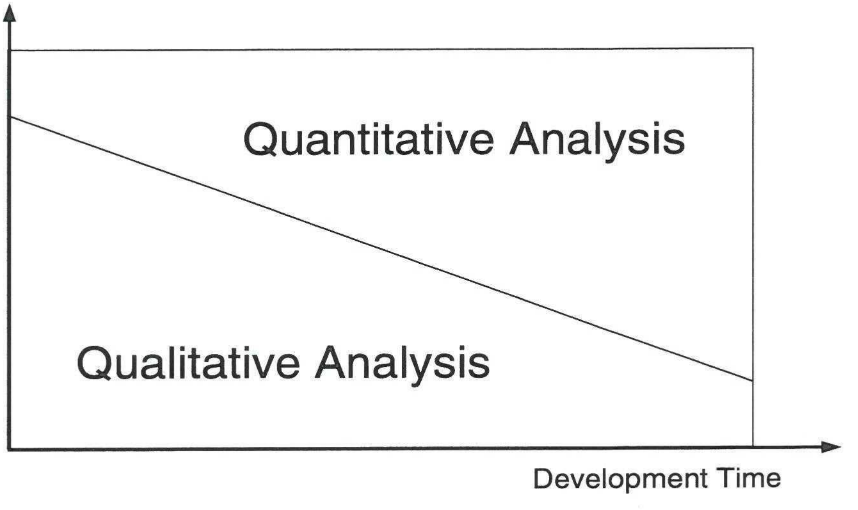

FIG. 1. Shifting needs of qualitative verses quantitative analysis during the product development process.

Development of the communication system shortens lead time and allow better tools, with higher accuracy, to be used in the product development process. Hence, developing an integrated system is beneficial for *both* early and late stages in product development.

2.2 Development of a jet engine component

In figure 2 it is illustrated how a solid model is being used as a common data source for several different activities in a product development project of an jet engine component at VAC. Although this approach requires both time and CAD resources, it has several advantages:

- Reduced total modelling time for engineering analysis tools
- Only one current version of information
- 3D pictures were helpful in presentations and discussions

- Accurate measurements were continuously used for design, instrumentation (placement of gauges etc.) and assembly purposes.
- Manufacturing techniques (CAM) simplified production

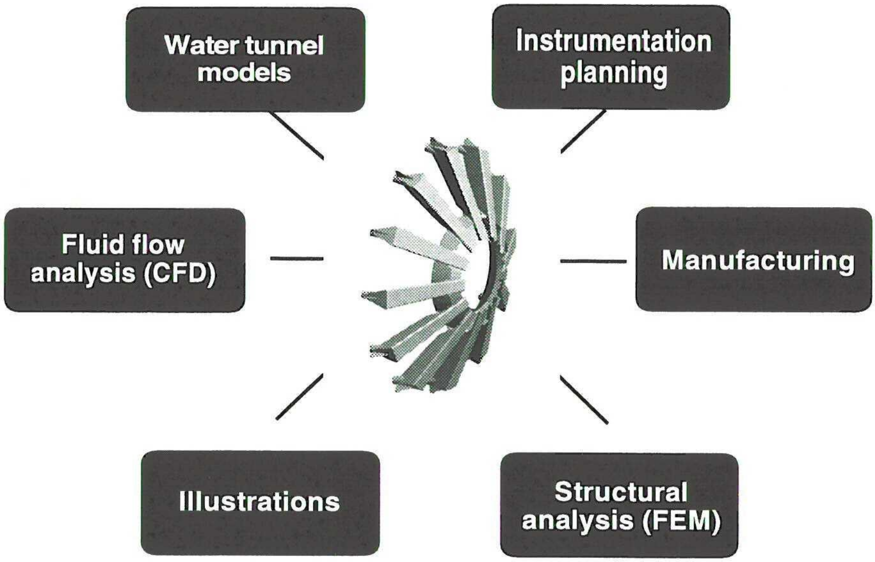

FIG. 2. Different use of a solid model in the development of a jet engine component at Volvo Aero Corporation.

Using a solid model was especially helpful since there was a significant amount of people involved along in the project, and only a few working full time (or nearly full time) on the project. There was never any doubt where the latest and most accurate product information was found.

3. Integrated thermal and structural analysis

In another example, life assessment of a gas turbine guide vane [11] was needed. The difficulties in describing the loads and the material degradation phenomena occurring during the operative cycle are two major obstacles in predicting life by numerical analysis. The assumption made here is that calculating heat transfer parameters in CFD results in a better load description, and thereby reduces uncertainties in the following structural analysis.

Although a problematic analysis situation, there are several motives for numerical analysis:

- Digital design iterations are cost effective compared to testing.
- Commonly, only a few test opportunities are given. Numerical analysis can reduce the number of design alternatives.
- Identification, planning and evaluation of interesting test parameters.
- Analysis is often the only way to continuously predict life for life cycle cost decisions.

Fluid analysis

The fluid flow pattern in a gas turbine is extremely complex, and not until lately the numerical CFD tools has been used in design phases. This is mainly due to long modelling and analysis execution times for sufficient accuracy of design problems. However, the perhaps best numerical way to predict heat transfer parameters at the component boundary appears here.

Thermal analysis

Within the component structure, the heat equation is solved using finite element methods, FEM. Conduction can be relatively well simulated, while the accuracy to a large extent depends on the boundary value description. This requires heat transfer parameters at the boundary. The result of the thermal analysis is the balanced temperature field (static analysis) or the evolution of the temperature field (transient analysis).

Structural analysis and life prediction

The temperature field history resulting from the thermal analysis causes the strains and stresses due to thermal expansion. Errors in thermal calculation can very well be accentuated here since the structural material model seldom is linearly dependent of the temperature under jet engine operating conditions. Together with the temperature and environment parameters, the resulting strains are used as a basis for life prediction analysis.

Integration

VOLSOL [12] is a general 3D CFD code at VAC, which is used for fluid flow analysis whereas ANSYS 5.2 [13] is commonly used for thermal and structural analyses of structures. Convective boundary conditions are used for the thermal analysis in ANSYS.

Heat transfer parameters on the boundary can be calculated in VOLSOL. Physically, the heat exchange between structure and fluid makes the problem coupled but at this stage only the mapping of results from CFD to FEM is of interest.

In this pilot system, heat transfer parameters calculated in VOLSOL is interpolated between the CFD boundary mesh and the ANSYS boundary mesh. The principle is illustrated in figure 3. The parameters are mapped onto the CFD boundary mesh and written on ANSYS format.

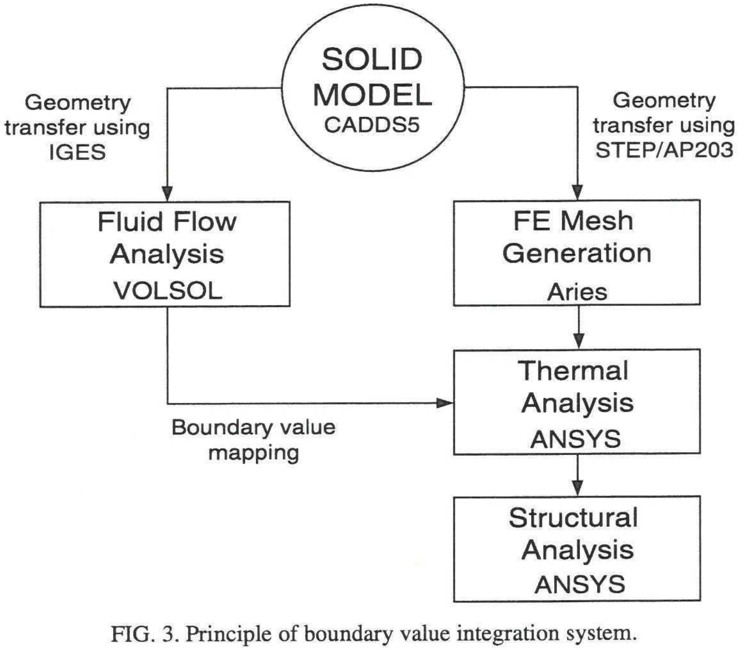

FIG. 3. Principle of boundary value integration system.

The solid model of the guide vane was defined in CADDS5 [14] and then transferred to Aries7.0 [15] using their STEP/AP203 interface. The FE mesh was defined in Aries and later used in ANSYS simulations. The CFD geometry was transferred from CADDS5 using IGES.

In this way, the same geometric model was used for both the CFD and FE model.

The loads mapped from VOLSOL to ANSYS were discrete surface loads, associated to the boundary nodes.

4. Results

Experience from using a solid model as a common data source in product development of a jet engine component was positive. The same source of information was used in most activities, which was one key success factor in the project.

As the same solid model was used for both the CFD and FEM models, the common boundary was well described. Node based results from CFD calculations were mapped onto an ANSYS mesh to describe the heat transfer boundary conditions. The CFD model of the gas volume is shown together with an ANSYS boundary mesh (shell elements) of the guide vane structure in figure 4.

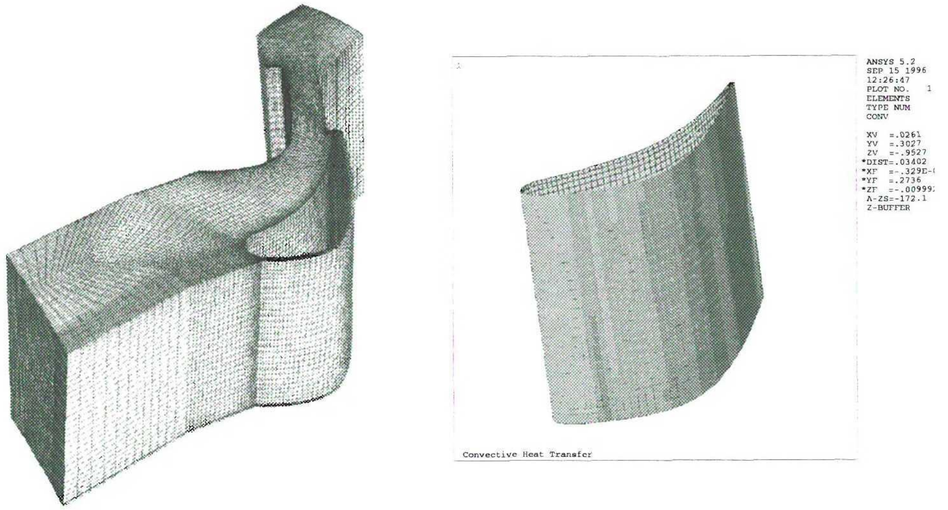

FIG. 4. The CFD (gas volume) 3D model where heat transfer parameters are calculated is shown to the left and the corresponding FE model (structure) including the boundary heat transfer parameters from CFD is shown to the right.

5. Conclusion and further work

Experience from using solid models in product development showed mutual benefits. As a common data source used in many activities the information exchange in the project was focused which was beneficial for project coordination. Using a common solid model as the source for geometry in CFD and FE applications simplified the integration of these tools.

Heat transfer conditions predicted in CFD were used as input in FEM analysis. This effort in trying to improve the load description can be motivated if improved accuracy in stress calculation (and eventually predicted life) can be achieved.

STEP technology seems promising in providing a common information environment, even though the application protocols may need to be extended to be able to handle the relevant information. Information models defined in EXPRESS [16], which is the language used to specify the normative part of all the information models in STEP, provides a technology neutral and implementation independent way of defining neutral formats.

Finally, introducing research results step by step, is a way to implement research results in an industrial process. In this example, the demonstrator system will be followed by more stable solutions using new technology and standards.

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Paper C

A Generic Methodology for Computational
Support in Product Development

Submitted for publication

A Generic Methodology for Computational Support in Product Development

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SUMMARY Computational support using advanced engineering simulation is becoming a more essential part of the design and development process. Requirements on computational support, however, differ during different stages of the product development phase. The requirements on how to conduct the computational support steam partly from the project situation and partly on the problem to be studied. In early stages of the development phase, little is known about the forthcoming product and the time for design iterations and analysis is short. As development work progresses, more information and details becomes clear and more efforts can be motivated and afforded for thorough analysis.

To clarify the role of computational support during such different product development situations a generic computational support process (GCSP) description is proposed for computational support. This generic process can be used independent of the problem- or project- situation and is therefor a suitable platform for communication and methodology development. It is also suitable for analysis of the critical parameters for optimising further development work.

The generic process is described and exemplified in the area of computational life prediction of a jet engine, and worked through for a life prediction of a gas turbine guide vane.

1. Introduction

Computational tools and techniques are increasingly being used in product development projects. Better use of computational techniques and tools is regarded to have a big impact on product development processes and practices to reduce lead time, increase quality and to provide a cost effective way to derive and analyse properties and functions of the product under development. In this paper a methodology to make computational support more effective in different situations of the entire product life cycle is presented and illustrated by an example from the aero engine industry.

A company commonly describes its product development work as a process, called the product development process (PDP). How well the company can develop products is a critical feature of competitiveness, and hence the development of the development process itself is important [1]. In aerospace business the task is to develop cost effective products in shorter and shorter time. Besides shortening development lead time, improving quality and flexibility while keeping development as well as total product cost low are imperatives for developing even more efficient processes. Best practice in product development has been conceptualised into methods such as Concurrent Engineering (CE), Integrated Product Development (IPD), Integrated Product and Process Development (IPPD) and others. They all have in common that the complexity and multi-disciplinary characteristics of product development work must be effectively organised and managed. To capture old knowledge in a recorded and retrievable for is an important task for rationalizing design and development [2].

Obviously, there are numerous of ways in which development processes can be improved, and this paper addresses only one, namely how to make computational support more effective to derive and analyse information about the forthcoming product within an integrated product development environment.

Computational tools in this context are computer aided simulation tools based on numerical methods such as the Finite Element Method (FEM) or Computational Fluid Dynamics (CFD). As will be described, their role during development differs depending on the situation.

Also, the intense evolution within the area of computers and computer applications over the last 30 years or so, has provided engineers with new and powerful tools that are increasingly being used to aid the design process [3], especially in the aerospace industry [4]. Although the literature on computer use in product development is extensive [5] design methodologies and practises for computational techniques in development projects have not been studied to any large extent. Computational support has been a specialist activity, commonly separated from design work [6]. Most established text books on 'engineering design' and 'product development' [7,8,9,10] only briefly consider how to use computational tools in development. There are several industrial studies, especially from the aerospace industry, where the computer aided support environment has been in focus. Examples are the DICE projekt at GE [11] and design systems development in relation to the development of the US Advanced Tactical Fighter project at Northorp [12]. Although these projects mainly focused on the (important) information infrastructure problems of data management and transfer it was found that the interaction between the computerised environment and the development practice/method was quite important.

Traditionally, literature on computational tools and methods are mainly considering issues such as numerical performance and the capability to predict and describe physical phenomena and does not emphasise the role that computational methods have within product development projects. However, it has been argued [13] that errors in computational predictions for design situations are driven more by modelling simplifications than by solution errors. The importance of idealisations and simplifications in design analyses has also been emphasised by [14].

In this article, it is argued that by using a generic process oriented description of computational support during product development, product development work can be significantly improved.

1.1 Product information evolution

Taking an information management perspective on product development, it is easily seen that information about (and related to) the forthcoming product evolves through the product lifecycle [15]. Initially, information is incomplete and not very detailed, and in addition heterogeneously structured [8]. As the process evolves, information is generated, matured and definitely increased about the product. Time frame for decisions are shorter in the beginning of a development project, whereas accuracy is critical in the later and more detailed stages of development. Also, the information about the product is less extensive in the beginning of a project than in the later stages. Some questions have to be answered over and over again during the progress of the project. For example; in all stages of development it is essential to know whether the product will meet the functional requirements or not. Methods used for analysis and information available may differ depending on the situation. The situation with repeating questions is illustrated in figure 1.

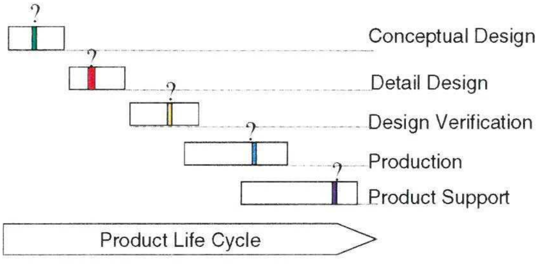

FIG. 1. Different phases of a product life cycle, where the same questions are addressed but with different objectives, information quality and solution method.

1.2 Levels of activities

Process descriptions are often used for project planning purposes. Design activities are then often considered as 'work packages' or 'design activities', characterised with a purpose, a lead-time and an actuator. Considerations of data needed and resources available are issues considered in the planning stage. At this level, details on how the design activity will be performed are seldom discussed. This level is shown as "Level 1" in figure 2. On an enterprise level, the entire product development process may be indicated as a single box, with an expected lead-time and required resources.

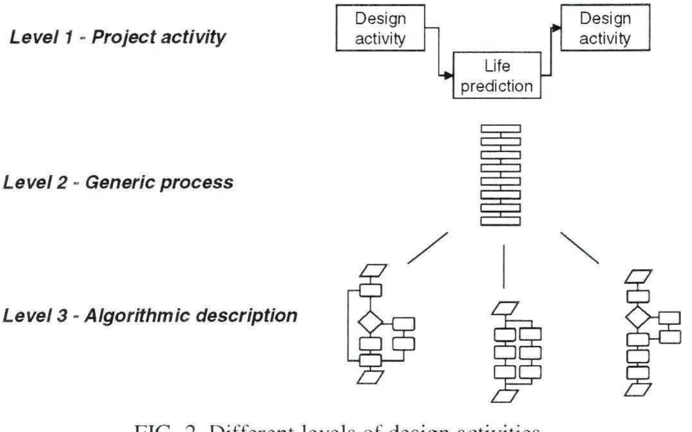

FIG. 2. Different levels of design activities

The actual work is carried out on a much more detailed scale of resolution. Descriptions of work tend to be more algorithmic, and sometimes these algorithms can be computer interpretable, and thus be automated. It is often beneficial to define algorithmic processes since these can be made into routine, and become lead-time efficient. The drawbacks of these algorithms are that they tend to become quite situation dependent. This level is indicated by "Level 3" in figure 2.

Going from the planning level 1 to actually carrying out the task on level 3 requires that the implicitly stated requirements in level 1 type of information are translated and interpreted to a full specification on level 3. By careful analysis of these issues, needs can be identified and interpreted on a more detailed level [16].

Commonly, this 'translation' requires experience and insight into both the higher level (Level 1) and lower level (Level 3), and one characteristic of a good designer is that he or she can choose the most relevant method (Level 1) that meets the needs in any situation (Level 3).

2. Generic process development

The approach in this work is to find a process description that is situation independent, with respect to information quality, but can be used to address one specific type of question that appears repeatedly during several different phases of product development. A process description, insensitive of in-data and actuating methods is here called a *generic process*, see level 2 in figure 2.

2.1 Generic activities

Computational support can essentially be decomposed into a number of 'generic' activities which constitutes a process, a Generic Computational Support Process (GCSP). An activity describes *what* has to be done as defined by the problem formulation. Each activity operates on information from up-stream activities together with additional (new) information specific to the activity. Often, different *methods* can be used to perform this operation in the activity. A *methodology* is needed to choose the best method for a given situation. These ideas are thoroughly described in the area of Design Science [2].

An activity is defined as generic, i. e. *situation independent*. Each activity needs a method and data. These methods are *situation dependent*, and cannot be formulated as generically as the activities. The relation between a generic activity and its associated data and methods is described in figure 3.

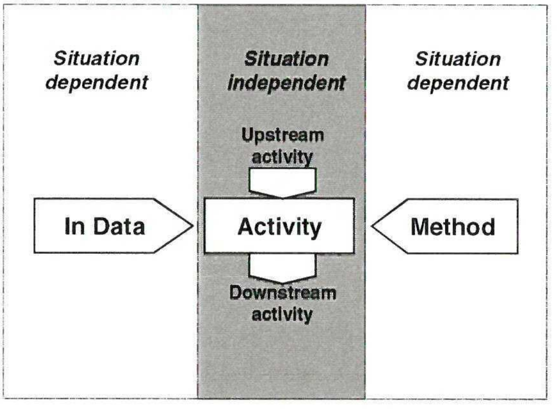

FIG. 3. A generic activity description in which the situation independent (generic) activity is separated from the situation dependent method and input data.

To define a generic process, activities must be separated from specific methods used to perform the activities.

2.2 Generic process

All activities have the same structure and they can be linked into a process, which describes when the activities are performed in relation to each other. Results that are produced in one activity are then used as in data in the subsequent activity in combination with new data in the downstream activity. A series of linked generic activities form a generic process. The activities are linked so that 'Activity 1' must be performed in advance of 'Activity 2' since data generated in 'Activity 1' is needed in 'Activity 2' and so forth, see figure 4.

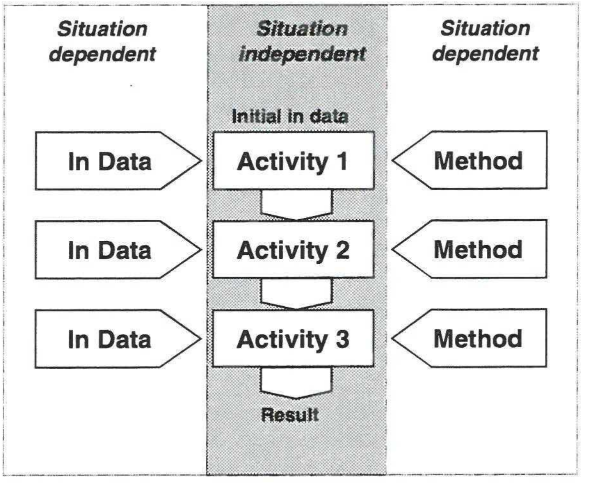

FIG. 4. A generic process is a series of generic activities. Results from activities are used as in data in subsequent activities.

For each activity there is a large variety of methods and data that may be considered. As a situation is applied, there is only a subset of possible methods and data remaining. The subset is defined by the situation, i.e. methods are situation dependent.

2.3 Applied generic process

The generic process view (figure 4) alone adds only limited value, and must be substantiated. In this paper, the interest is computational simulations of mechanical products and a GCSP is presented in figure 5. The process is still problem independent for a certain class of computational problems.

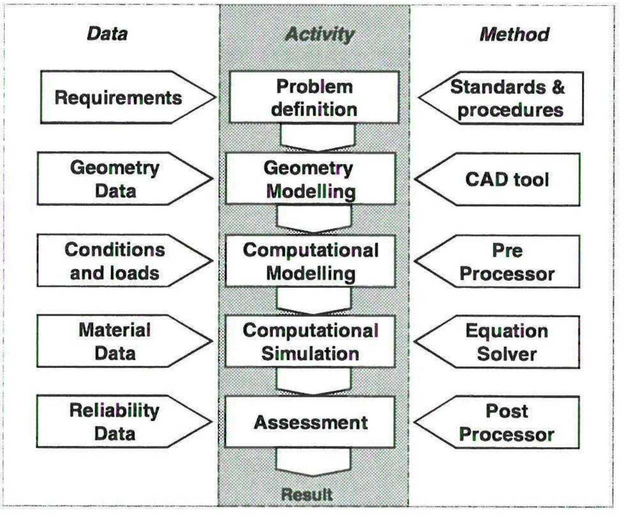

FIG. 5. A generic computational support process (GCSP)

These five steps must be conducted to perform a computational simulation of a mechanical product. After the *Problem definition* a *Geometry model* is needed as a basis for a *Computational model.* The computational model is defined so the *Computational simulation* can be performed and finally, an *Assessment* of the simulation results must be made. Each of these activities must be performed in succession, although iterations frequently may occur. These iterations are, however, situation dependent and are therefore left out in the generic description.

3. Use of generic processes

3.1 Customise the generic process

One may argue that the generic process seems to be sequential and does not support the iterative nature of most design and analysis activities. However these iterations appear as the process is customised by applying the generic process to a situation. The process then becomes algorithmic and most often situation dependent. Figure 6 shows the generic process applied to an algorithmic description with iterative steps of a life assessment process. When the process is customised, sub-activities can be defined since it may be necessary to decompose the generic activities and define others, support activities. One example of such a support activity is the derivation of boundary condition data, which may need a more clear description when the derivation of boundary conditions involves several other activities. The *Computational modelling* activity in the generic process is decomposed into several sub activities in an algorithmic (context dependent) process that describes how CFD is used to derive boundary conditions.

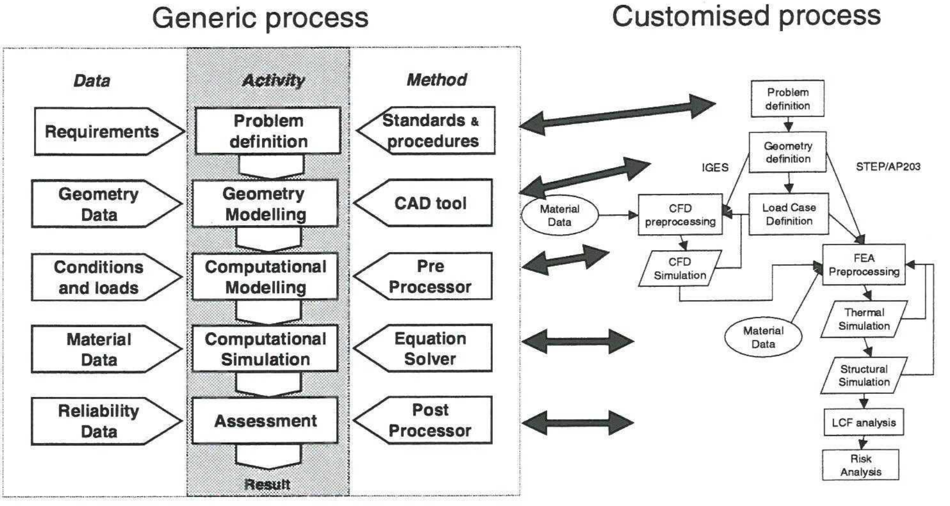

FIG. 6. Given the specific situation, the computational simulation may be algorithmic and iterative.

It is important to note that the customised process still can be described in terms of the generic process.

In a different situation, other activities in the generic process may have to be clarified when describing the algorithmic process. Conditions may for instance require the *Geometry Modelling* activity to be decomposed whereas the rest of the generic process is straightforward.

Other examples may be the activity to obtain material data, which may itself be an entire process, the *materials testing process*. The materials testing process is only considered to provide data to the core process in this respect, the computational support process.

3.2 Characterisation of methods

The objective with a computational simulation, together with the situation (available/obtainable data and methods) determines what is the best method to be used.

As the GCSP is used to support Product Development (PD), it is appropriate to use the general requirements on the product development process to characterise the methods in the GCSP. It is desirable to evaluate the effect that specific methods have on the progress of the product development process. This have been recently been studied by [17, 18].

Four general requirement dimensions on the methods used in the GCSP to support PD are;

- Short lead time
- High accuracy
- Low cost
- High flexibility

Characteristic relationships between these requirements for five different stages of the product life cycle are given in figure 7. The requirement on accurate and reliable predictions increases as the product goes through the development (and life) cycle. The figure illustrates how accuracy can be increased for each stage but to the cost of reduced flexibility. Cost and lead time for predictions does not necessarily increase though.

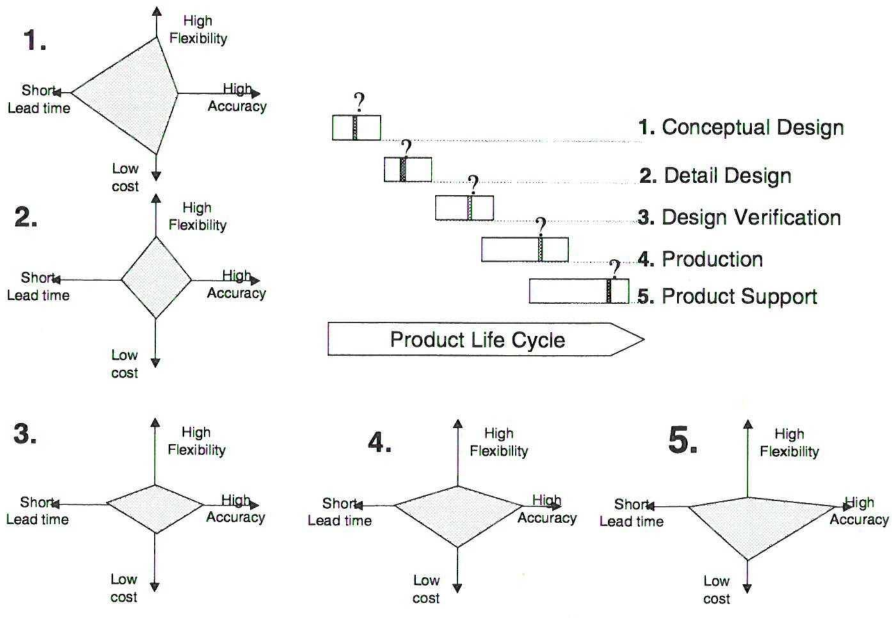

FIG. 7. Characteristic properties and measures for computational support methods in five different phases of the product life cycle of aircraft engines.

In early *Conceptual Design* stages it is vital to analyse and evaluate alternative designs concepts. Requirements are high on short lead time and flexible tools and methods. Information is typically incomplete which omits accurate predictions of the final product. Simple (non expensive), comparative predictions can be sufficient.

In *Detail Design*, the product is defined and analysed in detail. This requires extensive efforts in defining the geometrical and computational model, something that is often time consuming. Still, there are limitations in information and in-data. Uncertainties in predictions are still comparatively high.

In the *Design Verification*, verification of accuracy dominates. Correlation with engine rig tests is often possible, and refinements of computational models are made to reduce uncertainties. Often, the extensive modelling can be avoided, and previous models can be updated. Accuracy is improved by better information.

In the *Production* and *Product Support* stage, statistical methods are be used in combination with the computational simulations which further increases confidence in predictions. The disadvantage is that the flexibility of the methods is vanishing, since the statistical information improving accuracy is information that is valid for one configuration only.

3.3 Advantages with a generic process methodology

The most important feature of the proposed generic methodology is the separation between situation dependence (data and methods) and independence (activities). This is needed to obtain a sustainable and flexible approach to describe computational processes at a company. In accordance, the description is independent of computer implementations. This can be compared with the separation of an information level and an implementation level of an information model within the promising STEP [19] standard and especially the EXPRESS language [20].

Since the description is generic and applicable in several different situations, the method

- formalises a diverse and complex field and provides an overview
- can be used to identify the critical path so resources can be focused
- can be used as a basis for quality systems and for continuous development
- unifies terminology within the organisation and between disciplines
- is suitable for management and organisation of computational simulation activities

also, the generic process can be used for technology development purposes since it

- can be used to identify weak links of technology areas [16]
- supports modular development

Furthermore, the generic process has been shown to be useful for education and training since it

- reduces individual dependence
- provides a natural way of documenting results
- is suitable for education and training of engineers.

Finally, to obtain a competitive advantage for a company within an area of technology, knowledge sharing is needed [21]. A generic process description supports knowledge management in this respect.

4. Example - Structural Life Assessment of a jet engine component

The life assessment process constitutes of a number of distinctive activities. The *problem* is defined and an analysis strategy is outlined. A *geometry* model is needed that can be discretised for Finite Element analyses. A *computational model*, consisting of loads sequences, a discrete model (e.g a FE mesh) and analyses schemes is generated. *Thermal analyses* are made. A good description of the thermal field is vital for many engine components since high temperature and temperature gradient cause thermal fatigue [22]. The *mechanical analyses*, which are based on the structural loads and thermal fields then results in information of the stress/strain field. Once the temperatures and stresses/strains are known, various *life prediction* models can be used to predict the component life. Different models are used depending on the situation, e.g. crack propagation models, crack initiation models and oxidation models. Finally, the predicted life must be assessed using some reliability model in a *risk analysis*. Uncertainties in the data used, assessments made and accuracy of methods used have to be taken into account [13,23]. For analysis of existing components, field experience data can be used to perform the risk analysis.

Life assessment of components is made in early as well as late stages of design, and is an example where methods and data used for analysis are context dependent whereas the design question is generic and remains the same.

4.1 A generic process for life assessment

Applying the generic process described in figure 5 to the situation just described for life prediction of jet engine components results in a data and method independent description of computational life assessment.

A life assessment system for jet engine components described on this generic level is shown in figure 8. The output from each activity is used as input in downstream activities. For each activity the additional data needed are shown on the left side and the methods used within the activity are shown to the right. Data bases and their source activities are also shown in the figure.

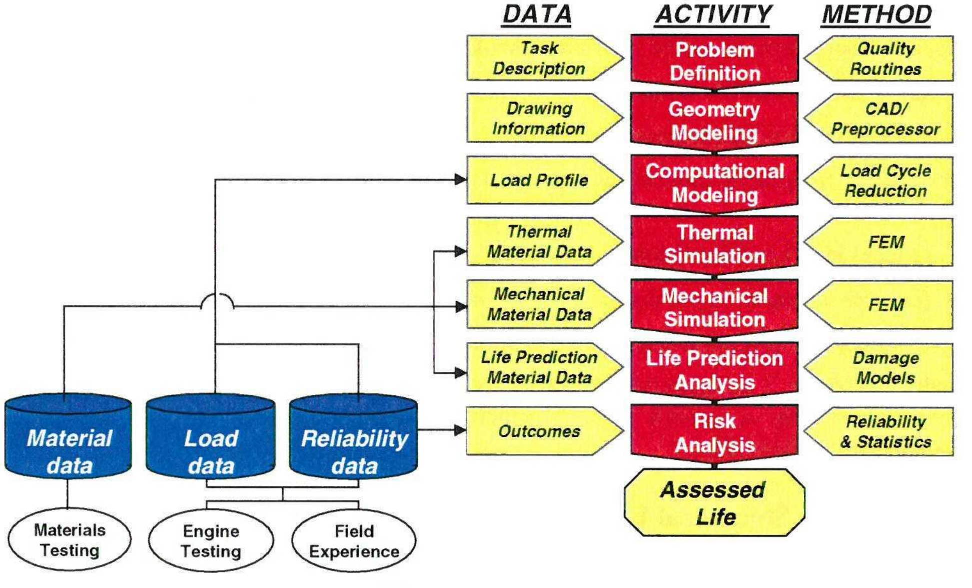

FIG. 8. A GCSP for structural life assessment

A more detailed description of the constitutive parts of the generic life prediction process is given in appendix.

4.2 Simulation of a turbine guide vane

Life prediction of a gas turbine guide vane will be used to illustrate the generic process in figure 8. The guide vane is shown in figure 9.

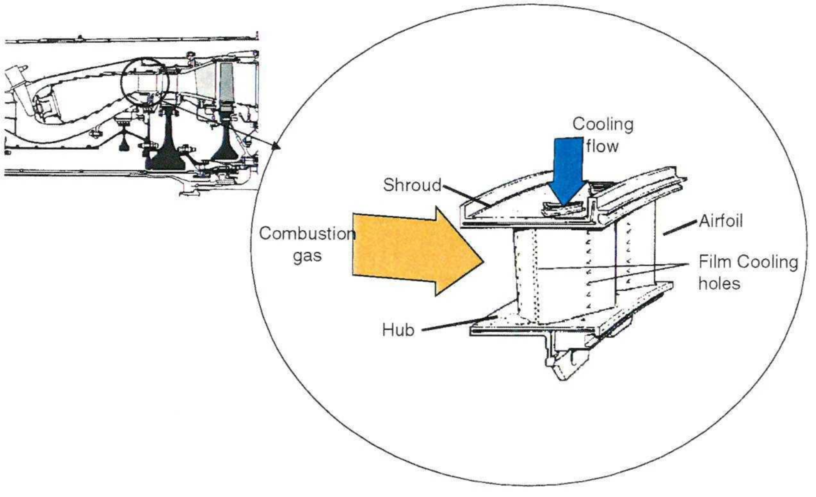

FIG 9. A first stage cooled turbine guide vane of a jet engine

The guide vane is exposed to hot combustion gas and is cooled by air from the compressor, since the combustion gas is significantly higher than the material melting temperature. It is a hollow structure made by a Ni-based superalloy and several cooling principles are used, including film cooling of the surface, where the cool air is let out through small holes. The vane is also impingement cooled, which is a technique to use forced convection on the vane wall from the inside.

The hollow vane thus experiences large thermal gradients, which causes large strains. During the engine operating cycle, each material point experiences thermal cycling. This phenomenon is called thermal fatigue and is one of the dominant failure modes for cooled high temperature components [22].

The purpose of the analysis here illustrates the use of the generic process. Hence, not much attention is paid to the accuracy of the analysis, neither will there be any experimental comparison of the results. The situation can be compared with an analysis in a conceptual design stage, see figure 1 and 7. The only addition in this example is that some field experience is known from a similar component. This situation is also typical since many new concepts are more or less related to existing products.

Problem definition

From service experience and engine endurance tests a set of outcomes where cracks frequently initiate on a similar guide vane is known. The objective is to find out the impact on component life due to local film cooling effects. It is desired that a result should indicate how significant the effect from film cooling is. The geometry model can be made quite simple, and the load cycle steps are coarse. Cyclic thermal strains are assumed to be the dominant damage mechanism, and a low cycle thermal fatigue analysis (LCF) will be performed. No other loads will be considered and there are no regulations or laws applicable at this stage. It is noted that the thermal load situation has to be carefully described since this is the load causing the expected failure mechanism. An algorithmic description of the GCSP chosen is given in figure 10, which has been derived from the generic process.

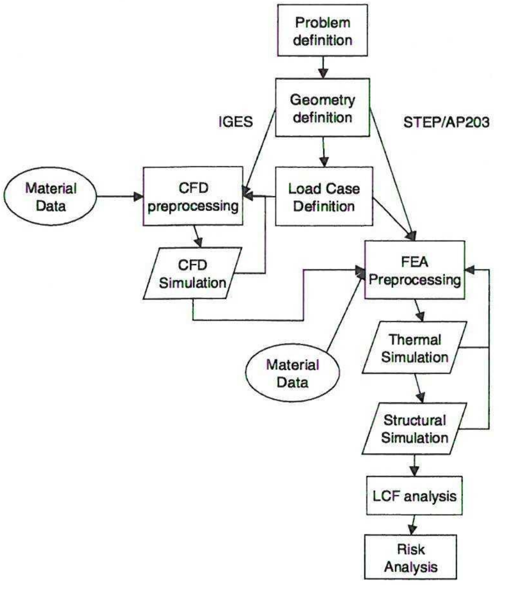

FIG 10. A life assessment process derived from the generic process for the guide vane example

Geometry definition

A careful airfoil description is needed to obtain a good description of the thermal field from the CFD analysis. The airfoil is modelled in a CAD tool (CADDS5™), but the rest of the geometry is highly simplified. This simplification is seen in figure 11 with the real geometry to the left and the simplified geometry to the right. The STEP AP203 format is used to transfer the geometry to the FE pre processor, whereas IGES is used the neutral format when transferring to the CFD pre processor.

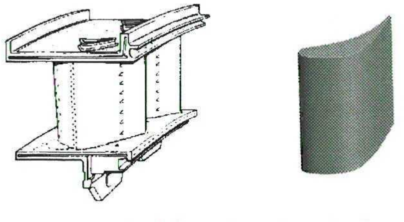

FIG. 11. The guide vane geometry to the left and the simplified geometry used here to the right.

This simplification is likely to introduce errors and increases the difficulties when assigning boundary conditions, but is sufficient for illustration purposes.

Computational model

The loads are basically proportionally to the levels of thrust of the engine. Commonly, the thrust varies extensively during flight, but can be more or less reduced. Here, the load profile is reduced to include only four thrust levels. Only stationary loads are considered. The sequence consists of 18 load steps during a 40 minute flight, see figure 12.

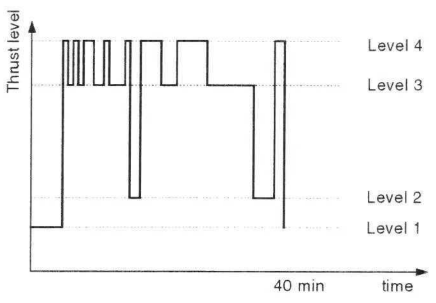

FIG 12. A fictive operating cycle of a military jet engine (thrust vs. time)

For each thrust level, the turbine inlet temperatures and pressures were used as input to a CFD simulation which resulted in a thermal load on the guide vane. These results will then be used as thermal boundary conditions for the thermal structural simulation. The CFD boundary mesh is shown in figure 13.

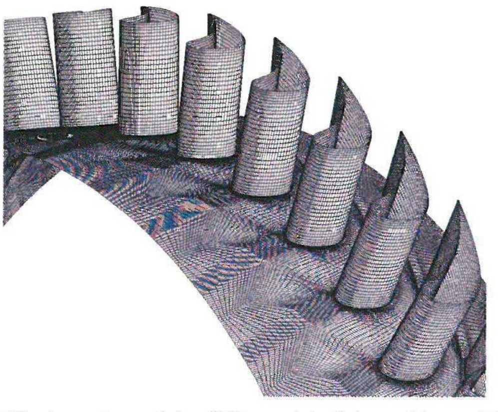

FIG. 13. The boundary of the CFD model of the turbine guide vanes

A radial distribution of the inlet gas temperature profile was used, see figure 14. Constant surface temperatures were assigned rather than taking into account the coupled thermal effect, which introduces a heat load uncertaity factor of about 30% [24]. Film cooling effects were represented by special boundary conditions and the CFD simulation resulted in a heat load on the structure for each thrust level. The heat load was represented by bulk temperatures and convective heat transfer parameters on the vane surface. The heat transfer conditions were mapped onto a FE mesh and used as boundary conditions for the thermal analysis [25].

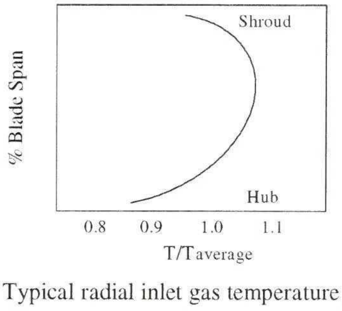

FIG. 14. Typical radial inlet gas temperature profile used

Thermal analysis

The objective with the thermal analysis activity is to solve the thermal problem as defined in the computational modelling activity. Stationary thermal analysis for the defined load steps where simulated in ANSYS™ [26] a general FE package. Temperature dependent orthotropic material data was used, i.e. the material responds differently in different directions of material orientation and for different temperatures. The result is a description of the temperature distribution within the material, which is used as input to the structural analysis.

Structural analysis

The objective with the structural analysis activity is to solve for strain and stresses as defined in the computational modelling activity using the thermal results. A linear elastic constitutive behaviour is used, although the material will experience strain levels causing inelastic stresses. This is compensated for later in the life prediction analysis.

Only the temperature load is considered, and temperature dependent linear material data is used.

Life prediction analysis

As the temperature and strain/stress field is known for each load level, the mechanical life prediction can be calculated. The linear stress history is evaluated for each node, and a Neuber rule is used for the plasticity correction [27]. Uniaxial and isothermal Low Cycle Fatigue (LCF) material data was used and the Palmgren Miner linear damage rule is used for the cycle evaluation. For the stress state evaluation, the maximum stress hypothesis is used. An in-house code, CUMFAT [28] is used where this process has been automated.

CUMFAT reads data from ANSYS result files and returns life prediction data for post processing in ANSYS.

Risk analysis

The life predicted in the life prediction analysis activity needs to be assessed in terms of uncertainty. The rough assumptions made in several steps of the process significantly reduce the reliability of this analysis. The geometrical assumption neglecting the hub and shroud makes the life predictions invalid near these boundaries. Thermal transients are not considered, although it is known that the largest stresses often occur during the transient. Also, only isothermal LCF data was used. This is not strictly a non-conservative assumption, but alternative approaches requires extensive materials test data which are seldom available until late design stages.

In figure 15 the assessed contribution to the total uncertainty by each activity is plotted together with the lead time contribution for each activity. Total lead time was three weeks (CFD analysis excluded).

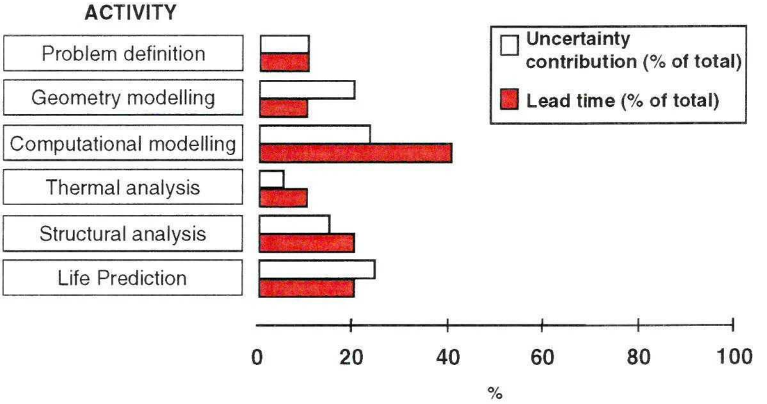

FIG. 15. Relative contribution to total uncertainty and lead time for activities.

The thermal analysis activity had a short lead time and low uncertainty contribution, but only included the FE analysis of heat conduction. Errors in the thermal field have been introduced in earlier activities. The boundary conditions were calculated during the computational modelling activity, which has a long lead time and still a comparatively high contribution to the total uncertainty.

Another note is that the geometry modelling activity had both low quality and short lead time. More effort in this activity would increase the accuracy of the activity.

4.3 Simulation results

The results are presented as the number of load cycles to crack initiation. A number of nodes from the mid section of the guide vane have been selected (figure 16), and presented in table I. The distribution of number of cycles to crack initiation is shown in figure 17.

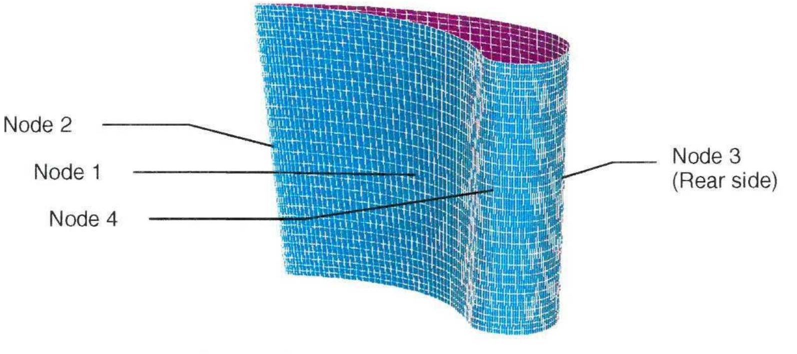

FIG. 16. The guide vane and identified nodes

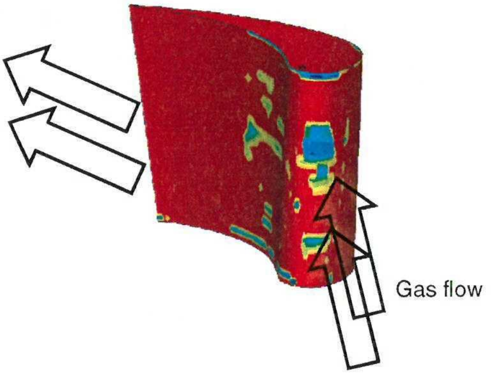

FIG. 17. Distribution of cycles to crack initiation. The blue areas have fewest cycles to initiation, and red has > 10000 cycles to initiation

The corresponding temperatures for each load level and the calculated life for these nodes are shown in table I.

Table I: Nodal results (Temperature in Celsius)

Entity	Node 1	Node 2	Node 3	Node 4
T (Load level 1)	708	785	711	405
T (Load level 2)	717	833	725	363
T (Load level 3)	879	1049	928	529
T (Load level 4)	767	1156	1071	1063
Life (Numbers of cycles)	10800	>10E6	>10E6	2682

The leading edge experiences large thermal gradients as it is effectively cooled on the interior side (impingement) while facing a high heat load on the exterior surface. For low thrust levels, the leading edge is cooler than the rest of the guide vane while at the highest thrust, the entire guide vane experiences high temperatures, exceeding 1100 °C.

It can be noted that the node experiencing the largest temperature difference between the load steps (node 4) has the shortest number of cycles to crack initiation. However, the node having the lowest temperature difference (node 1) also shows a low number of cycles to failure. This can be explained by that the global difference in temperature (leading vs. tailing edge) results in high stresses near node 1.

4.4 Analysis of methodology

For each activity within the computational process in figure 8 methods and data are used. Ideally, these should contribute to the total performance of the performed assessment. Figure 18 can be interpreted as that the performed assessment did not correspond to an ideal assessment. Data on accuracy and lead time have been extracted from figure 15, and complemented with information on flexibility and cost. Flexibility is judged from how flexible methods were used and cost in this case is directly proportional to the effort in man hours.

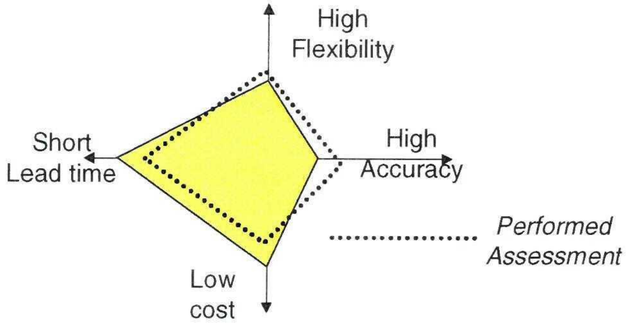

FIG. 18. Comparison between an ideal life assessment (compromise) and the performed analysis.

Targeting values on lead time and cost were not quite met, while accuracy and flexibility were slightly higher than necessary. The CFD simulation technique used introduced capability to account for the local film cooling effects which contributed to a sufficient accuracy to the cost of some extra lead time. The alternative, to not account for film cooling would be devastating to accuracy and other methods to include film cooling would be even more time consuming.

5. Conclusions and discussions

Life prediction and assessment is made in all stages of the product life cycle. A generic computational support process (GCSP) capable of describing all variants of life prediction used has been developed and used on an illustrative case.

A clear distinction is made between *situation dependence* and *situation independence*, which enables comparison between different life assessments with respect to their requirements from the product development process. Critical activities, data and methods can be identified in a structured way.

The generic process provides a sustainable approach to describe and continuously develop knowledge regarding life assessment. Furthermore, it is a good platform to perform uncertainty analysis and to identify the best possible approach to life assessment given any situation in the product life cycle. Thus, it provides a base for continuos development of computational simulations.

As this process based approach to life prediction has been used and developed at Volvo Aero Corporation, measurements of analysis quality and risk are naturally being incorporated. The system has been used for technology planning, where an overview is vital for identification of weak links in the analysis process chain.

Statistical risk analysis is straightforward where there exists enough statistical data. For risk analysis of life prediction where no experience data exists, the quality of assumptions made, and of the methods used, determines the reliability of the analysis.

The methods used for quality assessment of the activities in the guide vane example are as simple as they are subjective. More objective measurements of assessments, data and methods used have to be incorporated into the approach.

As new methods are being implemented, a methodology to qualify these should also be developed.

This method of using generic process descriptions has also been used for uncertainty analysis [23] and for integrating coupled analysis into the design process [29]. Furthermore the method is being used at Volvo Aero for designing the quality system for computational life assessment, and as a base for continuos development of technology and methods.

Acknowledgement

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Appendix: Step by Step description of a Computational Life Prediction Simulation Process.

Data	Activity	Method
	Problem Definition	
This is the data given as input to the computational support process and can be divided into *project data* and *analysis data*. In *project data*, limitations in time and resources for the analysis activity are given. The desired accuracy and how the analysis results are to be used are also input on a project level. Access to *analysis data* (Product information, load levels, materials data etc.) differs significantly depending on which phase the analysis is performed (see fig 1).	The objective is to decide on which analysis approach and what methods that are appropriate for the present situation. Important is to analyse the importance of the analysis [30], whether it is • Vital • Important, or • Advisory This requires different practices and methods.	There are a number of 'tools' available when determining the appropriate analysis approach. For failure critical parts, such as rotating components in jet engines, the analysis method is often prescribed by *standards and norms*. For non-critical parts, quality routines, handbooks, instructions and experience is used. The USAF's Engine Structural Integrity Program (ENSIP) [31] is one example of a standard specifying a damage tolerant approach for the life cycle of critical components. In *design* activities, different approaches can be used, such as fail safe, damage tolerant or safe life [32].
Data	***Geometry Modelling***	Method
Source data for geometry definition can be on quite different levels. From ideas and requirements of shape, weight, dimensions to already existing detailed solid models. The geometrical data existing must often be modified, either by simplifying or by generating more complete data. Examples of geometry data sources used for on data to analysis; • Sketches, non detalied geometry • Existing CAD models • Defined on drawings • Defined by measurements on the actual component	The objective is to define the geometrical information needed as a model. Depending on the analysis method chosen in the problem definition activity, it may be a 1D, 2D or 3D model. Commonly, the geometry to be modelled is a subset of a larger model or an assembly. These idealisations and simplifications must be assessed in terms of uncertainty contribution to the computational simulation.	If a geometric model has to be defined, it can either be defined in a CAD program, or directly in a pre-processor. Dedicated CAD programs often provide better geometrical modelling capabilities whereas pre-processors provides a natural coupling to the subsequent computational modelling activity. If a computerised model already exists, but in another format, it has to be transferred and often adjusted in the new software.
Data	***Computational Modelling***	Data
Boundary conditions, initial conditions and loads must be defined. These data are often difficult to derive and can be computed by other, *support processes* that may themselves include measurements, calculations of simulations. Examples used here are the use CFD to calculate thermal boundary conditions. Fatigue loads most often consists of a complex sequence of load levels, which must be decomposed.	The objective is to define the computational models so that can be executed numerically. The geometry is discretized and a mesh is generated. The loads are represented as boundary conditions and initial conditions for the different analysis method to be used. Depending of the chosen simulation approach, static and/or transient simulations must be defined. The computational modelling activity often iterates. For example, a static analysis may be followed by a transient analysis to achieve better accuracy, but the results from the static analysis is used as model input to the transient simulation.	Discretization is done by generating a mesh in pre-processors to the different analysis programs used (CFD and FEA) Measured loads may contain a very large number of load levels. Load cycle reduction techniques see e.g.[33] are therefore used to reduce the complexity in load data to a number of steps for comparison with constant amplitude test data. Methods to calculate/derive boundary conditions and initial conditions can range from hand calculations to sophisticated simulations correlated with measurements.

Continued...

Data	***Thermal Simulation***	Method
Thermal material data such as heat conduction, heat capacity and heat expansion together with the density of the material is needed in the temperature interval of interest. If the material undergoes phase change, the corresponding latent heat must be included as well.	The objective is to execute (solve) the thermal part of the computational model defined.. The temperature field and temperature history are then used as driving forces for the structural (mechanical) analysis.	Most commonly, the Finite Element method is used for solving the thermal conduction problem in the structure [34]. Note that radiation boundary conditions are non-linear with respect to temperature by definition whereas convection boundary conditions are linear.
Data	***Mechanical Simulation***	Method
Data used are temperature dependent material data for the constitutive stress-strain model.	The objective is to find the mechanical response to the load situation in terms of stresses and/or strains. This result is used as input to the life prediction. Gas loads and centrifugal loads are added to the thermal strains where applicable.	The stress analysis is most often simulated using Finite Element Analysis. The behaviour of the material is described by the constitutive model used. Linear, but temperature dependent response is the simplest adequate model for thermally dependent problems. There exist a variety of non-linear models, designed to capture different material behaviour. They are computationally more costly and requires more extensive material data.
Data	***Life Prediction***	Method
The stress/strain response for the material from the structural analysis is used as input. Other life reducing parameters may be included as loads at this stage. Examples are environmental loads (resulting in oxidation and corrosion) and correction factors for various other effects, not included in the thermal and structural analysis.	The objective with this activity is to predict the component life. The number of cycles to the component life measure is calculated. The life measure may be the appearance of a crack of certain length or the complete failure of the component function.	There are many methods to predict the component life. Typical mechanically defined approaches are • Stress - life approach • Strain -life approach [35] • Fracture mechanics approach [32] Each approach has their advantages and disadvantages [33]. For complex loads, environments and materials, the strain life is widely used and for critical and damage tolerant methods, fracture mechanics approaches dominate since they are better physically motivated.
Data	***Life Assessment***	Method
Three types of data exists; • Experience data from similar designs • Statistical data based on assessment and measurements of the simulation process constituencies. • Statistical data, based on product life from operation of component tests. In earlier phases, mainly low quality data is available and assessments must be made through careful analysis of the analysis process.	The objective is to evaluate the simulation results and determine the risk of premature failure of the component. A statistically assessed component life is the output from a life assessment. In early design stages, there is no direct experience from service and the risk analysis has to be focused on assessment of the analysis. In late design and during product support, service field data can be used for a statistical evaluation.	*Uncertainty* of the computational simulation can be made using quantitative analysis methods which are statistically based [13,23] *Risk* analysis evaluating the criticality of the simulation results and can be made by qualitative methods such as FMECA and others [36].

Paper D

A Method for Uncertainty Quantification in the Life Prediction of Gas Turbine Components

Fatigue Design 1998, Espoo, Finland, Vol 1, pp39-48

A Method for Uncertainty Quantification in the Life Prediction of Gas Turbine Components

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ABSTRACT A failure in an aircraft jet engine can have severe consequences which cannot be accepted and high requirements are therefore raised on engine reliability. Consequently, assessment of the reliability of life predictions used in design and maintenance are important.

To assess the validity of the predicted life a method to quantify the contribution to the total uncertainty in the life prediction from different uncertainty sources is developed. The method is a structured approach for uncertainty quantification that uses a generic description of the life prediction process. It is based on an approximate error propagation theory combined with a unified treatment of random and systematic errors. The result is an approximate statistical distribution for the predicted life. The method is applied on life predictions for three different jet engine components.

The total uncertainty became of reasonable order of magnitude and a good qualitative picture of the distribution of the uncertainty contribution from the different sources was obtained. The relative importance of the uncertainty sources differs between the three components. It is also highly dependent on the methods and assumptions used in the life prediction. Advantages and disadvantages of this method is discussed.

1. Introduction

Volvo Aero Corporation has a responsibility over the entire life cycle for a number of jet engines and engine components. This requires continuos efforts to monitor and predict the expected life of the engines and their components, as well as improving the products by re-design and development efforts. Since a mechanical failure in these products can have severe consequences, which cannot be accepted, high requirements are raised on engine reliability. Consequently, the methods used in prediction of expected component life must be assessable.

1.1 The life prediction process

Where no in-service experience exists, analytical life prediction methods have to be used. Often, these are based on deterministic predictions resulting in a single value. In generic terms, the life prediction process description is illustrated in Figure 1. This process consists of a series of linked activities, which requires specific methods and data depending on the situation. The degree of idealisation in the simulation model varies depending on the conditions for the simulation [11]. In each of these activities, uncertainties are introduced due to the scatter in the data and approximations in the methods used.

The generic activities in the middle uses methods (to the right) and data (to the left). Which methods and data that are used depends on the situation. The required accuracy together with available resources and data are the most important parameters deciding which approach to chose.

The *problem* set up has to be defined and an analysis strategy has to be outlined. A *geometry model* is needed as a base for the *computational model* which defines the conditions (loads, topology and boundary conditions). *Thermal analyses* are made since the thermal field is vital for many engine components since high temperature and temperature gradients causes thermal fatigue [2], and material properties may be highly temperature dependent. The *structural analyses*, which are based on the structural loads and thermal fields then results in information of the stress/strain field. Once the temperatures and stresses/strains are known, various *life prediction* models can be applied to predict the component life. Different models are used depending on the situation, e.g. crack propagation models, crack initiation models and oxidation models. Finally, the predicted life must be assessed using some reliability model in a *risk analysis*. Uncertainties in the data used, assessments made and accuracy of methods used have to be taken into account, which is being addressed in this work. For analysis of components where field experience exists, these data can be used to perform the risk analysis.

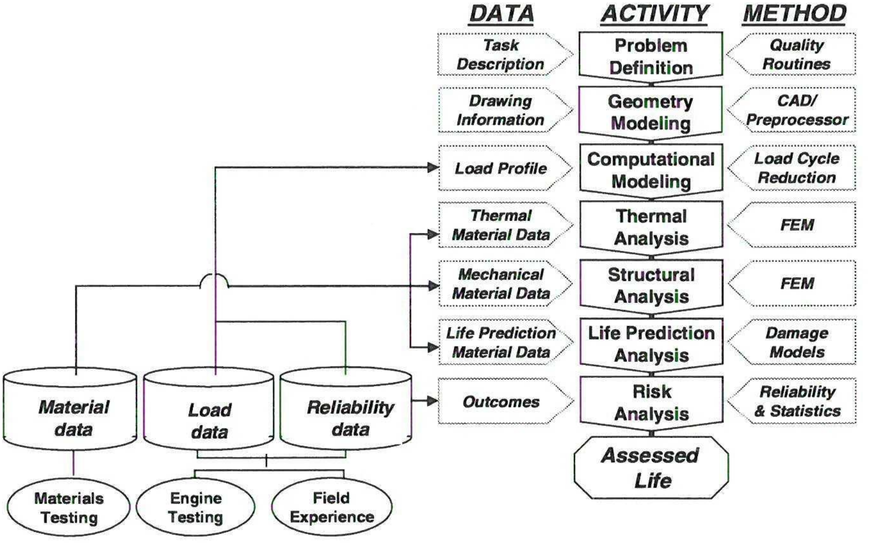

Figure 1: Generic description of the life prediction process at Volvo Aero Corporation, from [4].

Basically, uncertainties can be compensated for using conservative values in each activity in the process and obtain a minimal life. As an example, 1/1000 risk can be used for Low Cycle Fatigue (LCF) data as illustrated in Figure 2. This approach is undesirable since for most situations this lead to an oversized component, or an underestimated life.

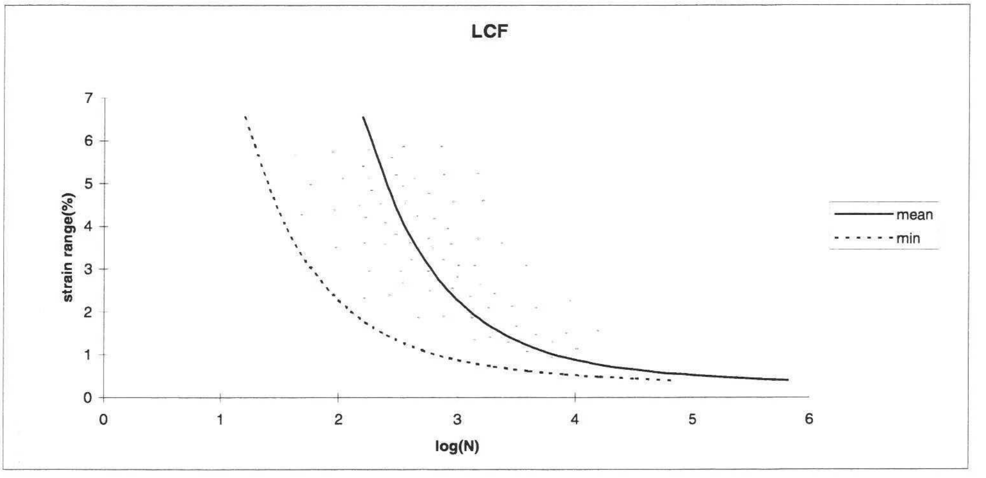

Figure 2: Strain range vs. life to crack initiation. The mean- and minimum-curves plotted in a statistically distributed data scatter.

Preferably, a probabilistic life prediction model, including the variability and uncertainty of the parameters, should be used. A probabilistic life prediction model results in a cumulative distribution function, for the estimated life rather than a single deterministically predicted value. Examples of probabilistic failure models can be found in [7] and [9].

In this work, the uncertainties introduced in each activity are identified, categorised, quantified and finally summed to obtain the total uncertainty of the entire simulation. This approach gives an idea of the effect from individual uncertainty sources on the predicted life, and critical parameters in methods and data can be identified.

The method has been applied on three different life predictions of jet engine components.

2. Method

The method described in this paper is derived from an American national standard (ASTM) for measurement uncertainties [3]. This standard specifies procedures for the evaluation of individual uncertainties, arising from random and systematic errors, and for the propagation of these errors into the final result. A similar methodology has been used for high cycle fatigue with variable amplitude in [8].

The activities considered are the four analysis activities in Figure 3. The figure illustrates the principle of uncertainty analysis in the situation where no field experience is available.

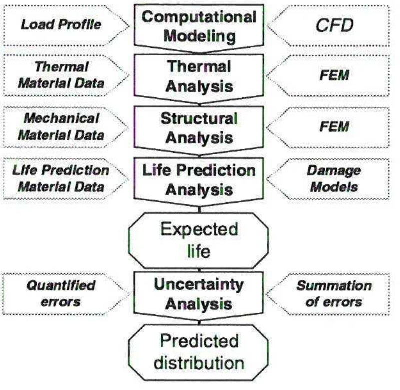

Figure 3. Uncertainty analysis applied on the life prediction process

A deterministically predicted life is obtained from the analytic life prediction and after the uncertainty analysis, an approximate statistical distribution for the predicted life is obtained. The methodology can be described in six main steps briefly described below.

2.1 *Identify the uncertainty sources*

The sources of variability and uncertainty have to be identified. In each activity the random nature of the input data and the approximations in the methods have to be examined, see Figure 4.

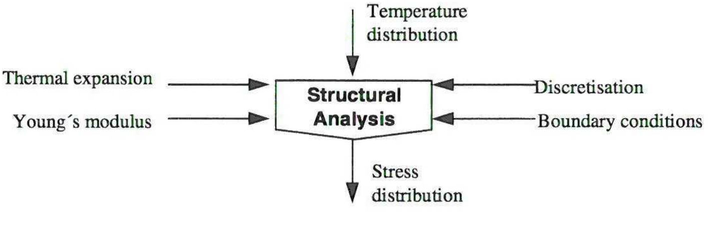

Figure 4. Inputs associated with uncertainties in an activity

2.2 *Categorize into random and systematic errors*

The uncertainties are either random or systematic. The random errors are due to scatter in the input data, e.g. the Young's modulus of the material. In our case, the systematic errors, or biases, are uncertainties due to approximations and idealisations in the methods used.

2.3 *Quantification of random errors*

The random errors are assumed to be normally distributed and are quantified in terms of the standard deviation. The scatter can usually be determined from measured data, but sometimes estimates based on previous experience must be used.

2.4 Quantification of systematic errors

The systematic errors (the biases), are constant in repeated measurements or calculations. In order to determine a bias exactly, it would be necessary to compare with the true value, which is usually impossible. However, it is often possible to estimate bounds for the error. Here, these errors are considered symmetric.

For the life predictions considered the systematic errors are due to idealisations [11]. The following methods for estimation are used. In order of preference:

1. Comparison of the calculated value with measurements.
2. Comparison of two methods of different accuracy
3. Estimation based on experience

The systematic errors are deterministic deviations, but in practise the magnitudes are unknown. Within the limited scope of this work the systematic errors are considered to be normally distributed random errors. The reason for this assumption is that we will allow an error of any size but the variance of the error is bounded. The most general distribution with bounded variance is the normal distribution in the sense that it maximises the entropy given the restraint of bounded variance. Using estimated maximum errors for the 95 percentile point, an approximate standard deviation is obtained by dividing this estimate by 2. Still, the errors are categorized in random and systematic errors since we are interested in separating the contribution from the two categories.

2.5 Examine the correlation between the uncertainty sources

The uncertainty sources may have a coupled effect on the predicted life. This effect have to be accounted for and is later introduced as a correlation.

2.6 Sum all uncertainties by Gauss Approximation formula

As the uncertainties are quantified for all activities their contributions are summed using the Gauss Approximation formula [6].

As an example, suppose that X_i are random variables representing the basic parameters with quantified uncertainties. That is, estimated values of the variances are available and the variance of Y is needed. If Y is related to X_i as $Y = f(X_1, X_2, \ldots X_n)$ and, the variance of Y is given by:

$$\sigma_Y^2 \approx \sum_i^n \sum_j^n \rho_{ij} \sigma_{X_i} \sigma_{X_j} \left(\frac{\partial f}{\partial X_i \partial X_j}\right) = \sum_i^n \left(\sigma_{X_i} \frac{\partial f}{\partial X_i}\right)^2 + \sum_i^n \sum_{j \neq i}^n \rho_{ij} \sigma_{X_i} \sigma_{X_j} \left(\frac{\partial f}{\partial X_i \partial X_j}\right) \tag{1}$$

where ρ_{ij} the correlation of X_i and X_j. The derivatives are calculated in the mean of the distribution of X_i. Since even the systematic errors are treated as random variables, (1) can be used for all errors. This gives an approximate standard deviation for the predicted life as well as quantified contributions to this standard deviation from each uncertainty source.

3. Examples

To illustrate the principle of the method, three case examples have been studied.

1. The combustor wall of a stationary gas turbine.
2. The flame holder of a military jet engine.
3. A high pressure turbine-blade of a military jet engine.

Each of these life prediction analyses has been performed at Volvo Aero Corporation under different conditions in terms of lead time and required accuracy.

In each of the analysis activities, a number of uncertainties are considered. Throughout the paper, only a critical point or area is considered, i.e. the point where failure is expected to occur according to the life prediction.

3.1 The combustor wall in a stationary gas turbine

The combustor wall is exposed to almost pure thermal load. Since the load in service is held almost constant, with long operating hours at high temperatures, the failure mode is creep.

Computational modelling. In this case this activity involves calculation of thermal boundary conditions using computational fluid dynamics (CFD), which predicts the fluid velocities and the gas temperatures along the combustor wall. The CFD analysis is followed by an energy balance calculation, in order to determine the heat transfer coefficients. The load is approximated to be constant at maximum, which is a good assumption in this case. The important output parameter from this activity is considered to be the heat flow, Q_{tot}, in the critical area.

The uncertainties in the CFD-analysis are due to uncertainty in performance data, geometry simplifications and discretisation. This causes errors in predicted fluid velocities and gas temperatures. The magnitudes have been estimated by specialists.

In the following heat balance calculation additional uncertainties are introduced as circumferencial variations are neglected and one dimensional heat conduction is assumed. An upper limit of the magnitude of these errors is estimated.

Thermal analysis. The uncertainties introduced in the thermal analysis are scatter in the thermal conductivity and systematic errors due to geometry simplification and discretisation.

Structural analysis. The uncertainties introduced in the structural analysis are scatter in the Young's modulus and the thermal coefficient of expansion. Systematic uncertainties are introduced due to discretisation, uncertainties in the mechanical boundary conditions and in the reduction of the of the multiaxial stress condition.

Life prediction. The time to creep failure is predicted using the Larson-Miller parameter [8]. The uncertainties introduced in this final prediction are scatter in the Larson-Miller parameter and systematic errors due to the use of this simple creep model and extrapolations. Also, creep may be the dominating failure mode, but neglecting other failure modes introduces uncertainty.

Propagation. The sources of uncertainty are identified and the magnitudes have been estimated by specialists. In order to sum the uncertainties the relation between the input parameters and the life are needed, i.e. the function, f, in (1) is needed. This function is quite complicated to derive analytically. However, only the derivatives are needed. In order to find the derivatives the serial structure of the life prediction is used. For example the derivative of the time to failure with respect to fluid velocity, u, is found by:

$$\frac{\partial \log(t)}{\partial u} = \frac{\partial \log(t)}{\partial \sigma} \frac{\partial \sigma}{\partial T} \frac{\partial T}{\partial Q_{tot}} \frac{\partial Q_{tot}}{\partial u} \qquad (2)$$

where t is the time to failure, σ is the stress in the critical point and T, the corresponding, temperature. Q_{tot} is the total heat flow through the wall in the interesting region. The logarithm is used since the life is known to be approximately lognormally distributed.

The factor $\frac{\partial \log t}{\partial \sigma}$ is derived from the Larson-Miller diagram. To find $\frac{\partial \sigma}{\partial T}$, the relation between the temperature and the temperature gradient in the critical point is needed. This has been found by pure reasoning. The relation between the temperature gradient and the stress is the coefficient of thermal expansion. $\frac{\partial T}{\partial Q_{tot}}$ and $\frac{\partial Q_{tot}}{\partial u}$ are found by setting up an energy balance equation for the heat flow through the wall and differentiate.

Correlation. For simplicity the correlation of the errors are assumed to be either 0 (no correlation)or 1 (full correlation). The error in temperature enters the life prediction in two ways. First, because the creep damage rate is temperature dependent and second, due to the thermal expansion, which causes a change in the stress. These contributions are clearly dependent, since they originate from the same source, and therefore $\rho=1$ is assumed. In all other cases $\rho=0$ are assumed.

Summation. Equation (1) yields the total uncertainty in the prediction in terms of the standard deviation for log(t). Since the total uncertainty is expressed as a sum it also expresses the contributions from each uncertainty source.

3.2 Flame holder in a military jet engine

The flame holder is located after the turbine, in the afterburner and its function is to create stable combustion in the afterburner. It is exposed to almost pure thermal loading and the failure mode is considered low cycle thermal fatigue [2].

The uncertainty analysis is carried out in the same manner as for the combustor. The main differences are the different failure mode and that the thermal boundary conditions were obtained by measurements. Furthermore, the stresses are above the yield strength for the material and a compensation for this is done by the Neuber-rule [5], since the structural analysis is linear. The life is predicted using the Coffin-Manson-Morrow equation [1].

The consequences for the uncertainty analysis are that instead of studying the uncertainties in the CFD-analysis the measurement uncertainties has to be considered. In the final life prediction, the magnitude of the error due to the plasticity is estimated by a comparison with a linear rule. No correlation between the uncertainty sources were taken into consideration.

3.3 A high pressure turbine blade in a military jet engine

The turbine blade is exposed to thermal, rotational and pressure load and the failure mode considered is low cycle fatigue. The uncertainty analysis is carried out in exactly the same manner as above. No correlation is assumed.

4. Results

In absolute terms the total uncertainty became of reasonable order of magnitude. The figures below shows the relative uncertainty contribution from the different activities divided in random and systematic uncertainties, in percent of the total variance.

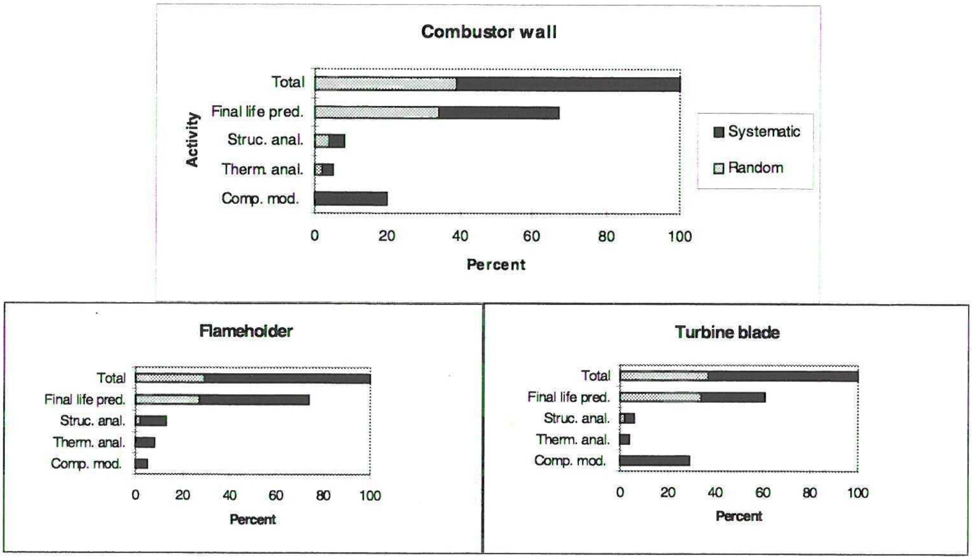

Figure 5. Relative uncertainty contribution from the different activities in the three cases divided in random and systematic uncertainties.

It can be seen that the prediction uncertainty is dominated by the contribution from uncertainties in the final life prediction. The random part of this comes from scatter in the life prediction material data and is the largest single uncertainty source in all three cases. The contributions from the finite element analyses are small. In the combustor analysis, the time to failure at maximum load is computed and the uncertainty in the load cycle reduction is therefore not considered. Thus, the contribution from the computational modelling is solely due to the uncertainties in the computation of the thermal boundary conditions.

In the flameholder analysis the thermal boundary conditions are measured and the uncertainty in the measurements are attributed to the thermal analysis. The uncertainty contribution from the computational modelling is therefore, (as opposed to the combustor analysis) solely due to the uncertainty in load cycle reduction.

5. Discussion

Regarding the presented results, several questions can be raised about the reliability of the uncertainty evaluation. Scatter in life prediction material data gives the largest contribution to the total uncertainty. This might be true, but the deviation between the real load situation and the approximated load situation has not been assessed in detail. Consequently, the predicted life is related to the simplified load history, not the real situation. This type of uncertainties are not thoroughly treated in this work, and should be the topic for further work.

6. Conclusions and further work

Several advantages and disadvantages can be identified using this method, see Table 1.

Table 1. Advantages and disadvantages using the presented method

Advantages	Disadvantages
Evaluation of the total uncertainty in the prediction is based on the sources of uncertainty.	Quantification of the elementary uncertainty sources is in some cases very difficult and may be extremely over-conservative or even un-conservative.
Results in an approximate distribution instead of a single conservative value.	Often, failures occur due to unforeseen failure modes, and this uncertainty cannot be included.
Highlights the problem of uncertainty.	

Ideally, this uncertainty evaluation method can be used to evaluate the reliability of analytical life predictions. At present the error estimates are to uncertain for the method to be used with confidence in design work. However, as for most structured methods, the major benefit initially is the accompanying discussion and communication between specialists and others interested in the result. The importance of this effect cannot be neglected. More work is required to ensure that the method becomes stable and reliable. Furthermore, a better way to represent different kinds of model errors and experience in the different error estimations are needed.

Finally, although there exists several difficulties and limitations it is a way to systematically address the issue of uncertainty evaluation of analytical life predictions. The underlying statistical treatment is straightforward, which justifies further work on the method.

The long time goal is to use a probabilistic model to incorporate the design parameters variability and uncertainty to obtain a cumulative distribution function for the life, instead of a conservative value, associated with an unknown risk level.

7. Acknowledgement

Life prediction calculations at Volvo Aero by Martin Öman, Joakim Berglund and Ken Spiers were used in the examples. Part of the work was financed by NFFP (Nationella flygtekniska forskningsprogrammet) project no NFFP347, and the ENDREA programme.

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Paper E

An Integrated Design Evaluation System Supporting Thermal-Structural Iterations

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An Integrated Design Evaluation System Supporting Thermal - Structural Iterations

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ABSTRACT In the design of high temperature components, design evaluation often requires an iterative procedure between thermal fluid and thermal structural simulations. An integrated computer system providing an iterative environment for the multi-diciplinary simulations required has been developed. The system supports iterations between thermal fluid and thermal structural simulations using two different commercial simulation packages. Traditionally fluid and structural analysis have been simulated separately and analysis of coupled problems has required special, multi-disciplinary simulation packages which are seldom used in early stages of design. Improving the infrastructure for data exchange between separate computer applications is one way to significantly reduce the lead time for design iterations. This reduction in lead-time allows multi-disciplinary effects to be accounted for in early stages of design. The design system is demonstrated on an exhaust manifold, where the thermal interaction between fluid and structure is of significant importance.

The commercial simulation tools have been integrated to demonstrate the effect of automised data flow on design methodology, i.e. design iterations. This integration method makes use of existing features in the simulation packages and uses an export file format as the neutral exchange format. In this way, the integrated system is simple and fast to develop which is preferred in small prototype systems and development project. Database integration supports a tighter integration, but requires more development effort. For design systems, where several design tools need to communicate, standardised information management procedures are preferable, following the ideas of the STEP framework.

1. Introduction

Business requirements for continous improvement of reduced lead times, increased quality and lower cost of product development are factors driving the development of engineering design systems and processes [1]. Decisions made during early phases of design have a big impact on the final product cost [2]. Design processes are to a large extent iterative in nature [3], and an increased number of well defined iterations have a direct correlation to product quality and performance [4]. Shorter development time implies lower development cost, and often the time to market is considered to be a competitive advantage [5].

The area of information management in engineering analysis applications has long been neglected in the management of simulation systems in design [20]. This has caused long lead times for communication of analysis data between simulation systems. Consequently, short lead time and an infrastructure which enables design iterations are two important features that must be supported by a design system.

1.1 Evaluation of design alternatives

Design can be described as the generation of alternatives followed by evaluation of these alternatives. Evaluation, following definitions by Ullman [6], implies both comparison and decision making. Often, computer simulations provide a relatively easy and inexpensive way of evaluating many different alternatives in a quantitative and objective manner. Alternatively, evaluations can be made using structured techniques (guidelines, matrix methods etc.) such as described in [7], [8]. Disadvantages using these techniques are greater influence of subjective comparison methods. Prototype tests are also considerable for evaluation, but requires hardware manufacturing and are often time consuming. Which evaluation method is preferable depends on the specific situation, but generally the simplest technique that gives sufficient design information is the best.

In the area of engineering design, simulation as an evaluation technique for early design phases is rapidly developing and has been identified as an important research issue [9]. Roozenburg and Eekels [10], consider simulation as the activity where values for evaluation are quantified. In the area of systems engineering [11], simulation has been used for performance evaluation more extensively than in the area of mechanical engineering.

The presented design system consists of two coupled design evaluation activities, the thermal analysis of a fluid volume and the corresponding analysis of the interfacing structure where the heat flux at the common boundary has to be iterated.

1.2 Information modelling in Concurrent Engineering

As an effect of the fundamental ideas in Concurrent Engineering such as increased parallelism and intensive cross functional team work, sharing and communication of information have become more complex [12]. Information is shared between teams, machines and processes [13], and enabling information sharing between these is important. This work primarily addresses the sharing of information between different computational tools, but the information to share is also strongly affected by the design process. Knowledge of which design iterations to support is needed to develop the appropriate information infrastructure.

The computational tools of interest here are most often dedicated to separate domains, one for fluid problems and one for structural problems. Fluid problems are studied using CFD (Computational Fluid Dynamics) while structural problems are commonly studied using FEA (Finite Element Analysis). CFD and FEA software are traditionally separated, but increased performance requirements on products, require the designers to account for the coupled physics already in the design stage and thus results in CFD are used as input to FEA and vice versa. Communication of data between these tools is thus needed in the design process.

Within each domain (fluid and structure) computational optimisation technique have frequently been suggested [14], [15], which highlights the importance of sharing information between systems. Finding the optimal design often requires the different analyses to be considered simultaneously.

In order to make the use of simulation in the design process efficient, improved integration between the simulation system and the design process is required [10]. This implies that domain specific tools need to be integrated.

1.3 Design iterations in the product development process

A design process is based on iterations between generating concepts followed by an evaluation. A good evaluation results in either a go-ahead decision or insights for further work on generating concepts. This is illustrated in Figure 1.

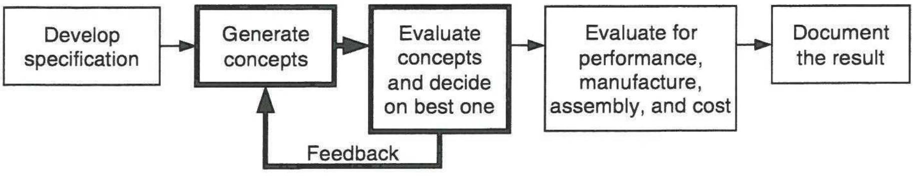

FIG. 1. Basic design process illustrating iterations (after Ullman [6]).

One definition of design iterations is the repetition of activities to improve an evolving design. Smith and Eppinger [16] conclude that there are two ways to accelerate an iterative development process, i.e. to execute faster iterations or conduct fewer iterations. The first alternative requires automation of the information flow and the second implies either improved accuracy in predictability or improved quality of feedback information.

The goal is not necessarily to conduct fewer iterations but to achieve a better result. As concluded in a study at General Electric [4], an increased number of early design iterations can improve the quality and performance of the product and can in turn reduce the life cycle cost of the product. Avoiding unintentional iterations by considering more aspects early, may have a significant impact on the leadtime.

1.4 Coupled nature of thermal and structural analysis

Park & Felippa [17] concluded already in 1983 that many engineering problems of interest require an integrated treatment of coupled fields and that considerable research efforts have been focused on the development of computational methods for mainly single-field problems. As the development of techniques for coupled systems requires multi-disciplinary expertise, it has lagged behind. Tougher design requirements emphasize the need for realistic computer simulations of coupled field problems.

2. Thermal and structural design iteration system

A system enabling iterations between thermal and structural simulations has been developed. The proposed system is illustrated by an exhaust pipe manifold design. Design requirements on exhaust manifolds in terms of low weight and structural durability are tough. To meet these requirements, the physical interdependence between the hot gas and the manifold wall structure has to be accounted for in design. The exhaust manifold is shown in Figure 2.

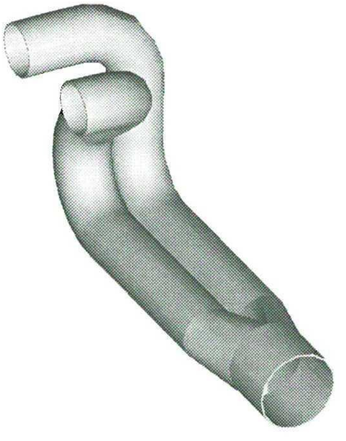

FIG. 2. Geometry model of an exhaust pipe manifold.

In the design process, CFD is used for fluid flow analysis to determine the heat flow and FEA is used to simulate the thermal flow and its effect on stresses and strains on the structure.

2.1 Design iterations

The analysis of a fluid-structure interaction problem can be obtained through a staggered solution procedure [17], in which separate fluid and structural analysis programs execute sequentially and exchange interface-state data such as temperatures at each time step according to Figure 3.

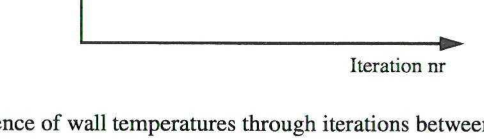

FIG. 3. Convergence of wall temperatures through iterations between thermal analysis.

Figure 3 shows the staggered solution procedure for the exhaust manifold example where the structural and fluid results are iterated until heat balance is reached. Once heat balance is reached, thermal stresses are analysed.

The thermal-structural design iteration activity is one part of the design process. In Figure 4 this iteration in the design process is illustrated.

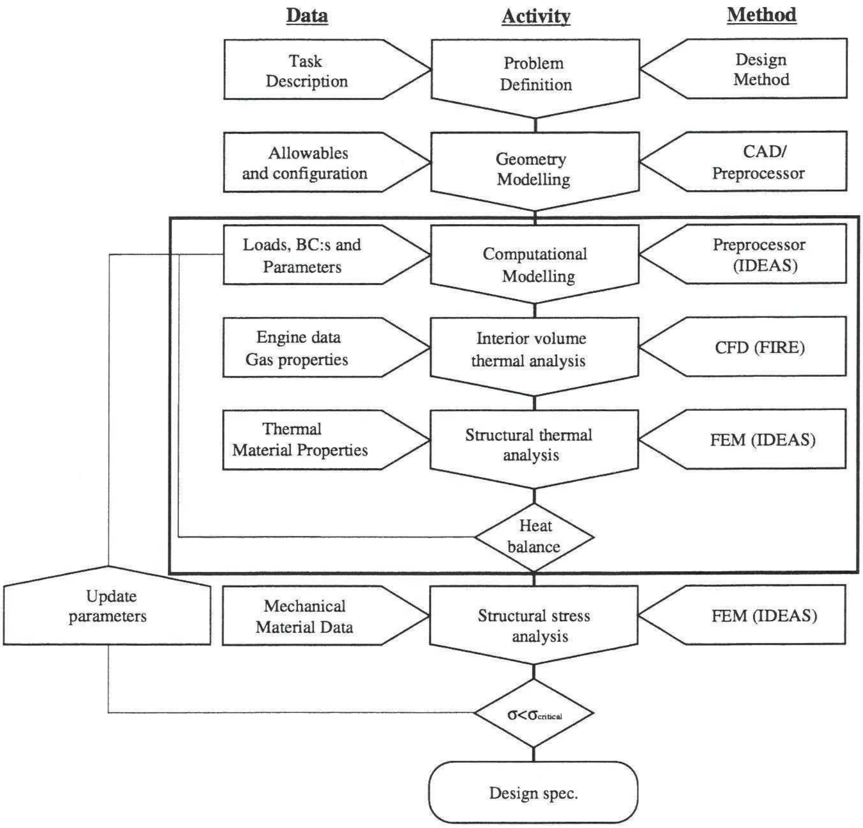

FIG. 4. Manifold design process.
The encircled area shows the iteration process where the design system has been used.

This method of process decomposition is described by Isaksson [18]. In the description, the generic activities are separated from the methods and data used. This way of describing the design process provides an overview of the design procedure, and separates situation dependent information (data and methods) from situation independent information (activities). In the specific product development process, simulation of thermal structural behaviour can be seen as one single design activity, where the objective is to evaluate one, or several, concept(s). The simulation activity can be decomposed into a series of linked activities, a process. Each activity requires data as input and uses some method or tool. The process view makes the simulation less individual dependent which is important for quality assurance of simulation. Further, it is a way to introduce experience and document simulations consistently in an industrial environment. The description is deliberately fairly abstract and the implemented design system is less generic.

2.2 *Product data exchange strategies*

In order to achieve communication between the computer tools used in the product development process different strategies have to be considered. Commonly two alternative strategies are being considered for communicating geometrically and computationally related data between CAE systems. Either by data translators between applications or by wrapping the applications [19], i.e. encapsulating the existing applications and mapping their internal information structure to a common standard.

Data translators can either be dedicated direct (point to point) translators or be based on a neutral exchange format [25], [26], [27]. This neutral format should preferably be a stable format which can be expected to exist for a long time. Generally, the more systems that have to communicate, neutral translations are preferable. For n systems, there are n*(n-1) possible direct interfaces compared to 2*n interfaces for a neutral format. For communication between only two or three points there are fewer interfaces for direct translators than when using neutral interfaces.

One category of neutral format is simply to use an existing format for one of the systems to be integrated. Another is to use neutral formats that are international standards, such as the STEP standard. While standardised STEP formats exists for certain types of data, such as solid geometry, standardised formats for engineering analysis data are not yet completely defined and commercially implemented. Significant work has been done [20], in the progress of STEP for Engineering Analysis. STEP will incorporate data associativity to the geometry model which enhances optimisation capabilities. Resulting geometry from simulation can be interpreted by the geometry definition instance.

2.3 Linking the design system

The CFD and FEA tools have been integrated to automise the analysis data flow. I-DEAS universal file format have been used as the neutral exchange format. The interfaces have been developed in-house and thermal analysis data are translated between the simulation tools using the different software formats. The design iteration system is illustrated in Figure 5.

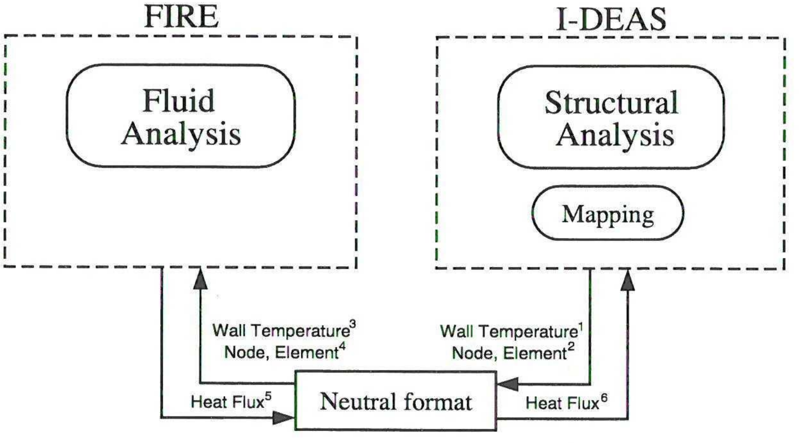

FIG. 5. Thermal and structural design iteration prototype system. The numbers are related to Table 1.

Fire [21] is a general CFD code used for fluid simulations and I-DEAS [22] is a Mechanical Computer-Aided Engineering (MCAE) simulation tool, used for thermal and structural analysis. Heat loads are analysed in CFD and used as boundary condition description for thermal and structural simulations in the MCAE simulation tool.

The MCAE program is also used as a tool for solid modelling, mesh generation, parameterisation and heat load mapping between the fluid and structural finite element meshes.

2.3.1 Activities

The activities for the design system are illustrated in Figure 4, and the different steps are shortly described below.

The non-iterative activities include problem definition and geometry modelling which consists of defining analysis approach and method followed by the creation of a parameterised solid model. The iterative activities include computational modelling and thermal and structural analysis. A discrete mesh is generated and boundary conditions are applied in the MCAE system followed by simulations in CFD and FEA. The thermal simulation activities are iterated until heat balance, which is followed by stress analysis. If needed the geometry parameters are updated for further iterations.

2.3.2 Implementation

The interfaces that convert analysis data are developed in-house, converting formats supported by the programs. The translated CFD analysis data are thermal results for the interior geometry. Because the MCAE system is used as the tool for generating the mesh, the interior FE mesh for the model is transferred from the MCAE as well as the results from the structural analysis mapped onto the interior FE mesh. The used software in/out formats and adherent entities are illustrated in Table 1.

Table 1: Software format description.

Software	In/Out - format	Entities	Format
Fire	In	Node, Element (Mesh)	Universal file v. 6[4]
Fire	In	Boundary Condition	Macro[3]
Fire	Out	Result	Ensight format[5]
I-DEAS	Out	Mesh, Boundary Condition	Universal file MS 5[1,2]
I-DEAS	In	Result	Universal file MS 5[6]

2.3.3 Mapping

The temperature boundary conditions are represented differently in the simulations. In the MCAE system the temperatures are represented as node values and the temperatures are applied as element surface values in CFD. The node temperatures are mapped to surface values by mean value calculation of the four temperature values surrounding a finite element surface.

Analysis data are mapped at the common boundary between structural and interior finite element meshes using an interpolation method in the MCAE system. Since the different meshes are generally incompatible, interpolation of data has to be done. The interpolation method, named data surface in I-DEAS, create a smooth data surface through the defining points, i.e. the nodes on the surface underlying the data surface.

3. Example: Manifold Design

An exhaust pipe manifold has been used as an example, to illustrate the design analysis system. One iteration of fluid and structural analysis of the exhaust pipe is shown in Figure 6. Analysis results as well as essential activities of the iteration procedure are also presented.

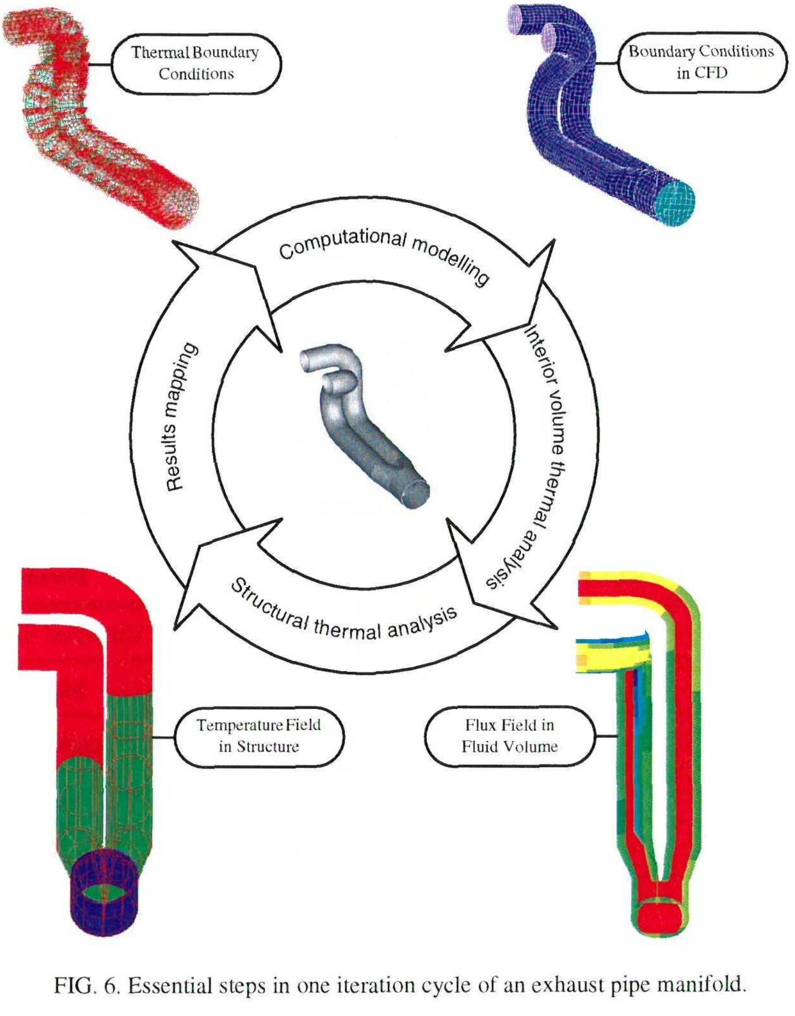

FIG. 6. Essential steps in one iteration cycle of an exhaust pipe manifold.

The computational model for the interior geometry of the exhaust pipe manifold i.e. finite element mesh and applied boundary conditions is transferred from the MCAE system to CFD. Additional boundary conditions are applied and analysed in the CFD system and the results are transferred to the MCAE system. The results are then mapped to the structure followed by structural analysis.

The different boundary condition representations in the simulation tools are shown in Figure 7. The left picture shows node temperatures in the MCAE system and the right surface temperatures in CFD.

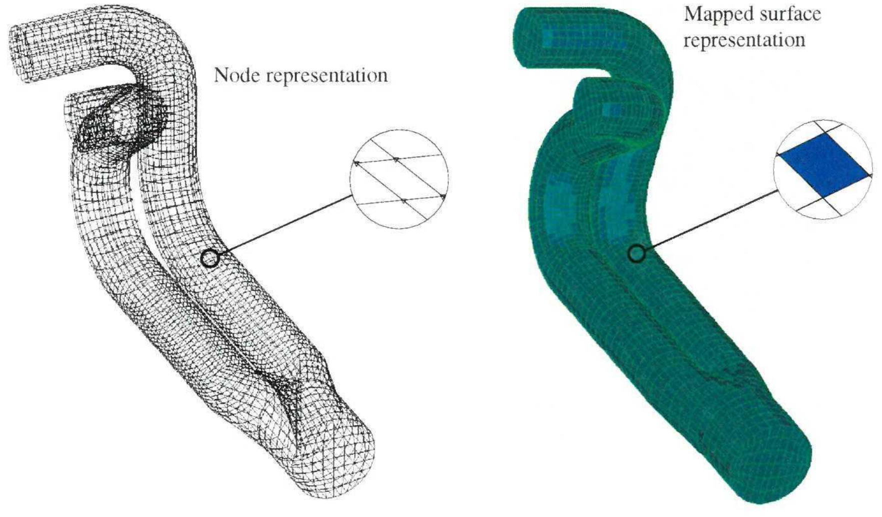

FIG. 7. Wall boundary values and interior exhaust pipe mesh from I-DEAS (left) transferred for fluid simulation in FIRE (right).

4. Conclusion and discussion

A design analysis system to support design iterations, where heat transfer conditions are used as input to finite element analysis has been developed. Heat loads are simulated in CFD which are used as boundary conditions for thermal and structural finite element simulations in the MCAE system. One iteration of an exhaust manifold has been shown as an example of the design iteration system.

The CFD and FEA tools have been integrated to automise the analysis data flow. I-DEAS universal file format have been used as the neutral exchange format. The interfaces have been developed in-house and thermal analysis data are translated between the simulation tools using the different software formats. Integration of commercial simulation tools improve the use and flexibility of specialized domain simulation tools in the design process.

To support the integration of specific applications like computer-aided design (CAD), finite element analysis (FEA), computational fluid dynamics (CFD) etc. in a computer-aided engineering design environment with a greater number of design tools, it is required that information can be managed efficiently. This includes the capability to share, transform, and exchange information between engineering applications by means of standardised mechanisms and protocols.

ISO 10303 is an International Standard for the computer-interpretable representation and exchange of product data [23]. It is important to provide a mechanism that is capable of describing product data throughout the life cycle of a product, independent from any particular system [24]. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving.

An example of a future design engineering environment is illustrated in Figure 8. simulation tools for optimisation, casting simulations and a separate general finite element code are introduced to this design system.

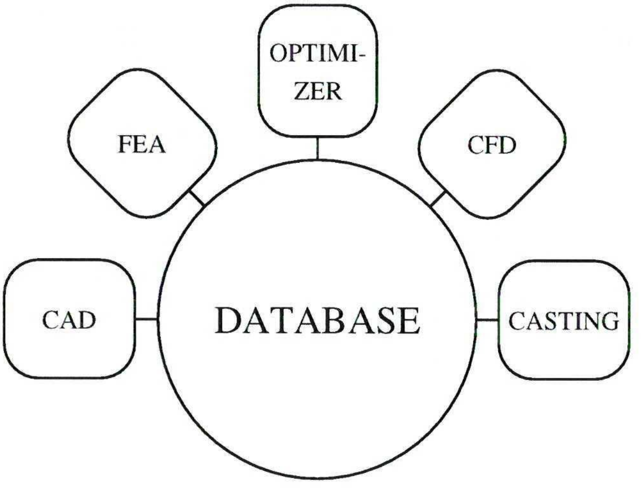

FIG. 8. Future computer-aided engineering design environment.

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Paper F

Evaluation of Design Process Alternatives
Using Signal Flow Graphs

Submitted for Publication

Evaluation of Design Process Alternatives using Signal Flow Graphs

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ABSTRACT The introduction of new design activities into an established product development process may involve more work in the initial stages of development. Yet this extra effort may reduce the need for more expensive and time-consuming redesign activities later in the project. We have studied a case where more intensive use of computational simulations in the early design phase means that fewer hardware tests are needed because the designs can be analytically evaluated in advance of physical testing. Total development lead time and cost can thus be significantly reduced.

This paper addresses how to evaluate alternative design strategies and methods with respect to their impact on the development process time. This is achieved by analysing the design process using signal flow graphs. The technique has been applied to jet engine component development projects at Volvo Aero Corporation in Sweden.

We have found that evaluating alternative processes using signal flow graphs not only is helpful to assess the effect of introduction of new or improved design activities on the development process, but it also is a means to facilitate the discussion of process improvement alternatives and tradeoffs for an organisation.

1. Introduction

When alternative product development methods become available, we need a rational way to choose among the alternatives. There are several reasons to introduce new activities within a product development process; these motivations broadly include reducing development lead time and cost, increasing process flexibility, improving product quality, increasing product performance, and reducing product cost. Suggested process improvements must be evaluated with respect to these goals. One important effect of a proposed new design technology may be to alter the completion profile of a product development process in terms of completion probability versus duration. Consider the following scenario which motivates this research.

Volvo Aero Corporation (VAC) in Sweden is a company which develops, produces and maintains aero engines, most often in collaboration with other engine companies. The aero engine industry is constantly seeking to improve the ability to predict technical performance and properties of their products. Computational tools for simulation of product behaviour are increasingly used to perform these predictions. However, these new design methods and strategies affect the flow and timing of activities within the product development.

Analytical tools such as finite element analysis (FEA) and computational fluid dynamics (CFD) are routinely used with the objective to develop more effective products. Use of these tools in design activities, however, is also an important characteristic for the efficient development process.

Often, decisions to introduce new methods and tools are based on 'soft' information such as management skill or personal experience [1,2]. Objective evaluation methods have mainly been restricted to software and hardware performance tests, and not focused on the effect that the tools may have on the development process. Making sound decisions for the introduction of new simulation technologies into the design processes therefore contributes to the ability of maintaining and improving competitiveness. To maintain control of actions in development situations is a key to competitive advantage [3]. In analogy with evaluating product performance using computer model simulations, evaluation of process performance using process simulation techniques is addressed in this paper.

Analysis of design process alternatives requires the options to be carefully understood and described. We argue that deeper understanding gained from analyzing the design process improves the decision basis for evaluating and selecting the best process alternative.

In this article, a method for evaluation of design process alternatives has been applied to development projects at VAC. The application area of interest is development of mechanical components for high temperature applications in jet engines. Development of jet engines and jet engine components requires extensive testing for both design and qualification purposes. Physical hardware testing in engines is both expensive and time consuming. It can be argued that simulation techniques can reduce the number of hardware tests needed since these simulations reduce the risk of late redesigns. Ideally, no redesign is necessary when the design is tested in the engine. The trend is to make several design iterations using numerical simulation tools, and to use physical testing mainly for verification and qualification.

1.1 Design process alternatives

There are many possible strategies to design any product, and the most capable firms continuously seek alternative methods in an effort to improve their development processes. Several authors [4, 5, 6, 7] have investigated how to understand and re-sequence existing design activities within complex development processes to avoid large design iterations.

Another approach to improve the product development process is to introduce new design tools and methods. Examples include new simulation techniques, prototyping methods, testing procedures, or analysis programs. In this paper, we compare alternative ways to utilise CFD analysis within the development process for jet engine components at VAC.

Two principally different CFD simulation support strategies have been investigated and compared to a reference case where no CFD simulation has been used. First, computational simulations can be used to enhance the quality of 'traditional' evaluation tests, such as engine rig tests. In this case, the simulation support is made entirely in parallel with an existing design activity, as an add-on activity. Second, computational simulations can be used directly in the definition of a product, i.e. prior to any hardware manufacturing. In this case, the simulations may become lead-time critical while they also can affect the hardware design.

1.2 Modelling design processes

The flexibility and quality of product development processes can be evaluated by modelling various features of the design process. Krausse et al [8] have incorporated resource constraints into a process model, and have addressed the coupling between resource management and development project planning. Adler et al [9] studied the effect of queuing where there is competition between projects for development resources. Eppinger et al [10] introduced signal flow graphs (SFGs) as a flexible tool to capture the effect of varying task success probabilities and task duration's on the lead times of development projects. Andersson et al [11] extended the functionality of SFG models by incorporating activity cost into SFG analysis in combination with a Monte Carlo simulation implementation.

To predict features such as success probabilities and lead times of the design process, the process must be modelled with sufficient accuracy. In order to capture the impact of the proposed design process modifications, the resolution of the model must be detailed enough to resolve the relevant design activities, yet general enough to enable comparison between alternative processes.

To predict the lead-time distribution, we chose to use the SFG method, as suggested by Eppinger, et al. [10]. We demonstrate by example that the necessary input data are obtainable and that the analytical results are helpful to evaluate the design process alternatives.

1.3 The role of design iterations

The mapping of an industrial development process into an analytical model highlights a number of challenges. Foremost, the role and interpretation of design iterations must be carefully considered since the process modelling inevitably includes simplifications and idealisations.

Development projects primarily follow a company-defined development process. The description of this process dictates the nominal sequence in which the many design activities are performed. In reality, the need to iterate (repeat) an earlier design activity is common. These iterations, i.e. return to a previous design state, are generally not represented within the prescribed design process and cannot be represented by standard project management tools and techniques. Furthermore, we have no models of changes in information quality as iterations occur.

To accelerate the iterative design process, Smith and Eppinger [4] suggested that either fewer iterations should be conducted or that iterations should be carried out faster. One conclusion from a study at General Electric [12] was that many short iterations early in the development process were preferable to a limited number of longer iterations. In the study, the total development lead-time was shortened from 18 to 7.5 months and the product quality was improved. Increased and/or improved use of simulation tools was suggested to improve design iterations in both of these studies.

In a discussion about the role of design iterations, it is helpful to distinguish between different types of design iteration. We describe design iterations using two dimensions: repetitive vs. evolutionary and intentional vs. unintentional. An explanation of these types is provided in table I and examples given in table II.

TABLE I. Terms used to describe design iterations

Term	Explanation
Repetitive	The design criteria and activity remains the same, whereas the design or design parameters are changed.
Evolutionary	If, when analysing the result of an iteration, new information alters the set-up of the design activity. New parameters may turn out to be important.
Unintentional	Unplanned iteration, required when an activity has to be repeated although the 'go ahead' criteria has been met.
Intentional	Planned iteration, e.g. first and second prototype or the iteration needed to converge, or meet the design criteria.

TABLE II. Examples of the four types of design iterations

	Intentional	Unintentional
Repetitive	E.g. Planned parameter study of wall thickness options.	E.g. Redesign when the intended design does not meet specifications.
Evolutionary	E.g. Planned simulation for identification of critical features, leading to new design criteria or a new simulation approach in the next iteration.	E.g. Redesign due to neglected effects of thermal expansion, leading to new specifications and new design tasks.

2. Signal Flow Graph Modelling

The signal flow graph is well known as a method for circuit and systems analysis in electrical engineering and for modelling discrete-event systems. Eppinger et al [10] suggest that SFG is a powerful tool to model and analyse product development processes, and they provide a more detailed explanation of this method.

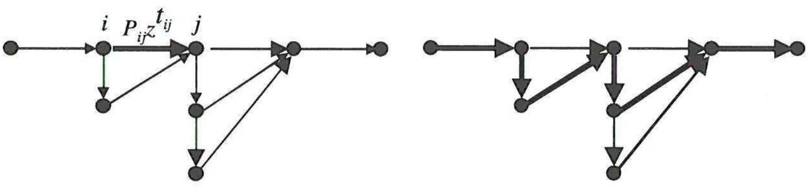

FIG. 1. A SFG schema of a simple process with iterations. A branch is highlighted to the left and a path to the right.

The signal flow graph is composed of a network of direct branches which are connected by nodes. (See figure 1.) The branches represent the design activities, and the nodes represent states of the process and may involve a probabilistic choice as to which subsequent branch to follow. The branch *jk* depicts the activity when going from node *j* to node *k*. Each branch is associated with a quantity known as the *branch transmission*, P_{jk}. The branch transmission include the probability to execute the task, p_{jk}, and the lead-time for the task, t_{jk}.

$$P_{jk} = p_{jk} z^{t_{jk}}$$

The transformation variable, z is used to separate time and probabilities when branch transmissions are multiplied. This is convenient for analytical purposes, since the probabilities are multiplied in the expression and times added in the exponent. The *path transmission* is then computed as the product of all branch transmissions along a single path. Using this representation is analogous to a discrete sampled data system for which analysis methods are well established.

The *graph transmission*, T_{sf}, is the sum of the path transmissions of all possible paths between a starting node s and a finishing node f. The graph transmission can be derived analytically, even for complex, iterative situations [10]. This expression is then differentiated and evaluated at $z=1$ to yield a series of terms of the form $p_i t_i$, summed over all paths, resulting in the expected value of the lead time.

$$E[L] = \left. \frac{dT_{sf}}{dz} \right|_{z=1}$$

We have used a numerical method (programmed using Matlab™) to identify all possible paths with a lead time below a given value. Since existence of iterations gives an infinite number of possible lead times, the result of the numerical method is a truncation. The accumulated probability is an indicator of the reliability of the answer as it asymptotically approaches unity.

2.1 *Modelling assumptions*

By necessity, there are many assumptions made when a SFG model is used. The first and major assumption is that the design process can be described as a number of design activities and design iterations. The second assumption is that it is possible to gather lead-time data for the design activities. How iterations affect the lead-time for the repeated activity is difficult to assess. Using project records is a way to obtain these data. Third, we assume that the task durations are accurately represented by deterministic quantities, so we assume that stochastic variations and queuing are negligible.

A fourth assumption is that we know the path probabilities. In situations where the process has been executed many times, statistical data may be available, and probabilities may be obtained with some confidence. However, it is our experience that the design process is often evolving and may be poorly documented. Where no documented data are available, or where the model is used to predict future effects, empirical data may be gathered through interviews.

2.2 *Comparing alternative design processes*

The alternative design processes should be described using the same level of abstraction, and the differences clearly differentiated. We have found it helpful to define a generic base model where the differences of interest are expressed as parameters or as added/removed activities. Criteria for evaluation must also be defined; in our case it is the lead-time to completion as a function of probability.

The alternative processes are then modelled as signal flow graphs, where values of lead time and success probability are assigned to every activity and iteration. The SFG analysis yields the distribution of expected lead times. Taking the accuracy of input data into account, the most appropriate design process can then be chosen.

2.3 Simple example

To illustrate the methodology, we consider a simple design process analysed using the SFG method. This simplified development process is described as three design activities: preliminary design, test and evaluation, and detail design, as shown in figure 2. We are most interested to model the effects of the iteration following the test and evaluation activity. This iteration results from the go/no-go decision taking place after testing. Each of the activities may involve many sub-tasks but this level of detail is not modelled. To simplify the analysis only design iterations over one design activity are considered.

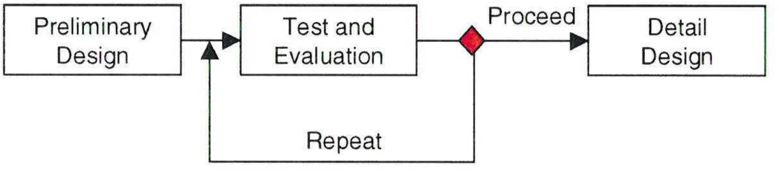

FIG. 2. A simple, iterative, design process model.

For the example design process, a simple SFG model is shown in figure 3. The model includes the lead times and success probabilities of the tasks.

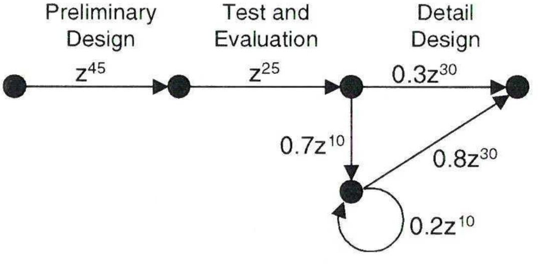

FIG. 3. A SFG model of the simple design process.

The process begins with preliminary design and the first execution of test and evaluation, taking 45 and 25 days, respectively. After the first 'test and evaluation' activity there is only a 30% possibility to proceed with the 30-day detail design activity. More likely (70%), a test and evaluation iteration is necessary, taking 10 days, after which there is an 80% possibility to go ahead with the 30-day detail design task. If more iterations are needed, these also take 10 days to conduct, and the possibility to proceed is 80% after each iteration. There is an infinitely small possibility of an infinite number of iterations, but the accumulated completion probability asymptotically approaches unity.

The result from the numerical SFG computation is a (truncated) list of all possible outcomes, i.e. a lead-time and a probability for each possible path through the signal flow graph. This list can be used to calculate the expected lead-time and to create a histogram of probability for different lead times. However, we find that the most interesting result graph is of the cumulative probability of completing the design process as a function of lead-time. This result plot is given in figure 4.

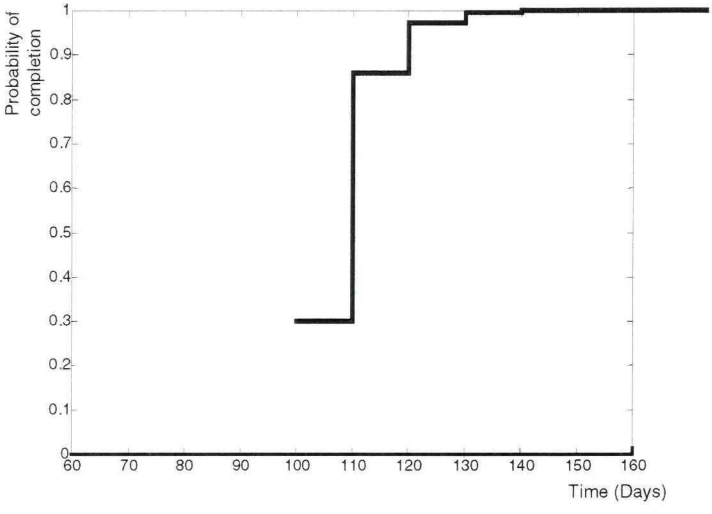

FIG. 4. Cumulative probability to completion as computed from the SFG model.

3. Application – Jet Engine Component Design

Development of a jet engine component consists of a number of *development stages* — typically a preliminary design stage, a detail design stage, and a qualification stage. The development stages are divided by critical decision gates, where stage repetition, project continuation, or termination is decided. Each development stage consists of a number of *design phases* where a design phase typically consists of *design activities* followed by *evaluation activities*. The number of design phases scheduled within a stage are the intentional (planned) iterations. A development stage with two design phases and two activities within each phase is illustrated in figure 5.

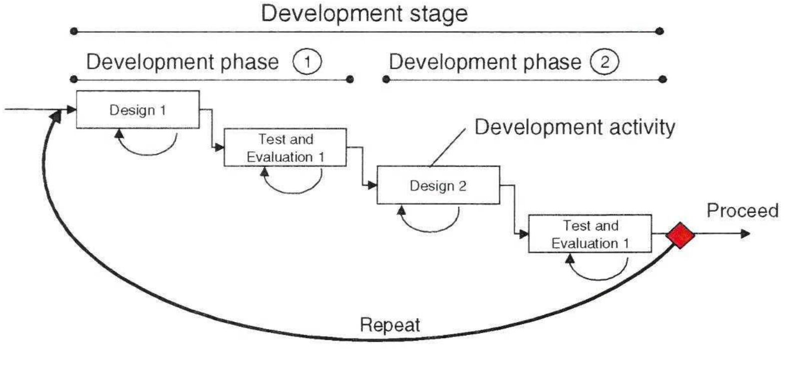

FIG. 5. A development stage with two development phases

The lead time and success probabilities of the development stages are critical for progress of the development project. Failure to meet stage exit criteria has a major impact on the development project and may terminate the project, or lead to expensive and time-consuming redesign iterations. Iterations within each development activity would have less severe consequences.

Use of computational simulation support such as CFD in design is a relatively new design process option. Historically, such support has not been possible. As CFD was introduced in development, these methods were mainly used for confirming evaluations and were not used for critical-path design activities. Experience and confidence was gained, and lately CFD has been used for design support, i.e. as a central activity directly affecting the component design (and the critical path).

We now compare three different component design processes for a single development stage at VAC. In these three processes, differing levels of computational support are used. Associated with each design activity are the appropriate task times and iteration probabilities. We compare the processes based on the overall expected lead time and success probability.

3.1 *Design process model*

To compare several alternative design processes, we define a parameterised process on an abstract level valid for all of the situations of interest. Changing the various parameters represents differences between the processes.

The three alternative design processes are illustrated in figure 6. The model describes a development stage including two design phases. As engine test activities are expensive and time consuming, including hardware construction, the two engine tests are planned and scheduled in advance. Even if the first engine test shows that the design does not met all the requirements, only minor design changes are possible within the same test activity. The fact that the second engine test already is planned allows larger design changes, based on the first test result, to be included in the second engine test. The two development phases can thus be seen as intentional/evolutionary iterations (as defined in tables I and II).

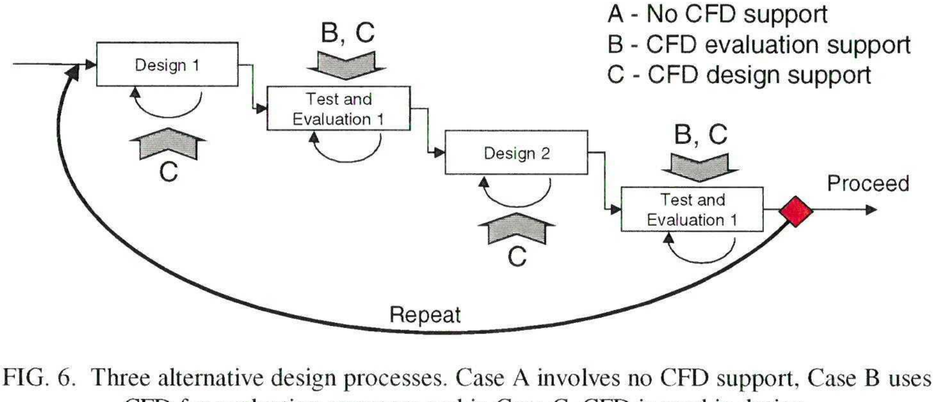

FIG. 6. Three alternative design processes. Case A involves no CFD support, Case B uses CFD for evaluation purposes and in Case C, CFD is used in design.

In process alternative A, no CFD is used during development. In process alternative B, CFD is used only to support evaluation of engine rig tests. CFD does not become lead-time critical, because it does not directly affect hardware design. In alternative C, CFD is used directly in the design process, so CFD iterations in the design activities are included in the model.

Activities D1 and T1 comprise the concept development phase of the project. D1 is the first design activity defined as the period from the program launch, through concept generation and definition until the design is frozen. CFD parameter design iterations are considered only in alternative C. No iterations are defined for case A and B, since these are not relevant for comparison.

T1 is the first engine test activity, which includes generation of manufacturing information (drawings), manufacturing of hardware, instrumentation and rig set up, engine rig test and evaluation of test results. Iterations, representing fixes, but no new testing hardware, take place in cases A, B and C.

Activities D2 and T2 comprise the refinement phase of the project. D2 is a design activity using input from D1 and T1 activities. T2 is the last test activity, followed by the critical decision to go-ahead to the next development phase, execute another test iteration, or to repeat the entire phase.

Ti1 and Ti2 are the incremental modifications within engine test, without new hardware manufacturing. Ti1 and Ti2 occur for all three alternatives. Di1 and Di2 are the CFD design iterations only. These CFD iterations do not include new major design, only parameter modifications of the CFD model.

3.2 SFG Model

A signal flow graph capable of representing cases A and B is shown in figure 7. Using null probabilities, the signal flow graph capable of representing C, shown in figure 8, is able to also model alternatives A and B. The SFG model is only considering 'Go Ahead' or 'Redesign' as options after the completed second test and evaluation activity. The 'No Go' decision is not modelled.

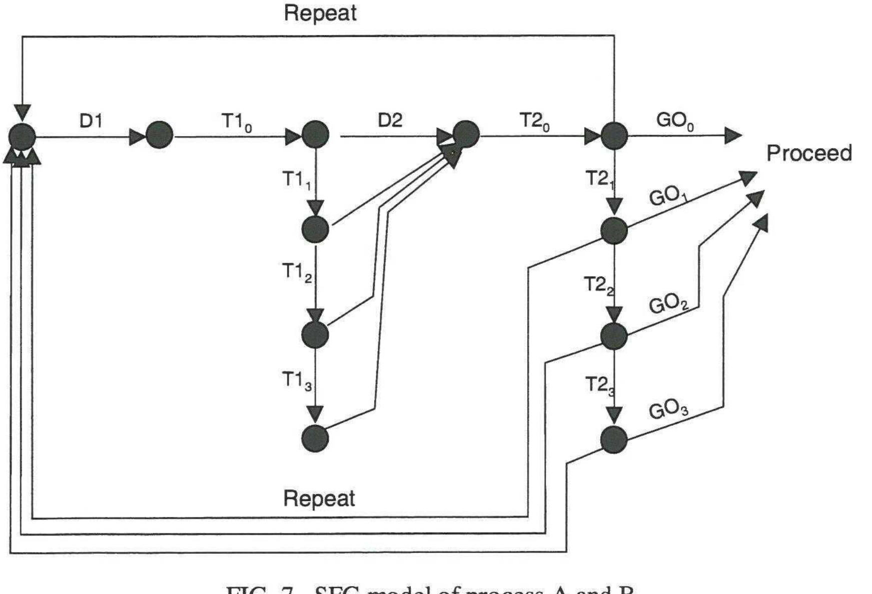

FIG. 7. SFG model of process A and B.

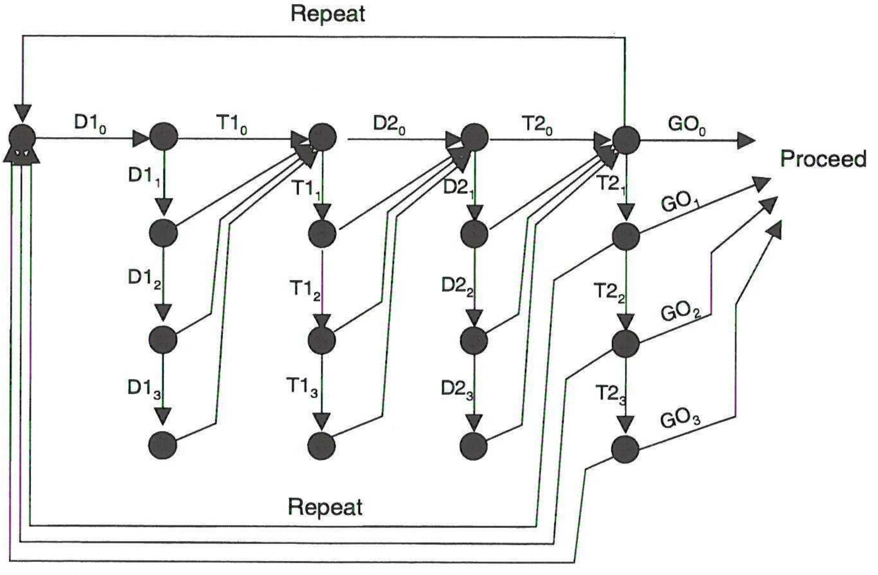

FIG. 8. A SFG model capable of representing all three design alternatives by parameter variation.

Each of the paths in the SFG model is assigned parameter values for probability and lead-time for their transmission functions pz^t, as listed in table III. For simplicity in figure 8, some of the paths leading to the first iteration of each activity are not labelled with indices; however, there probabilities are complementary to the other paths — the exit from each node must sum up to one. The lead times for these paths are equal to the $T1_0$, $D2_0$ and $T2_0$ respectively, as the lead-time of the first test or design activity is independent of previous design iterations.

TABLE III Parameter values pz^t for the three design process alternatives

Parameter	A	B	C		Parameter	A	B	C
$D1_0$	$1.00z^{45}$	$1.00z^{45}$	$1.00z^{75}$		$T2_0$	$1.00z^{150}$	$1.00z^{150}$	$0.70z^{150}$
$D1_1$	$0.00z^{0}$	$0.00z^{0}$	$0.50z^{10}$		$T2_1$	$0.70z^{5}$	$0.70z^{5}$	$0.10z^{5}$
$D1_2$	$0.00z^{0}$	$0.00z^{0}$	$0.35z^{10}$		$T2_2$	$0.50z^{5}$	$0.50z^{5}$	$0.05z^{5}$
$D1_3$	$0.00z^{0}$	$0.00z^{0}$	$0.00z^{10}$		$T2_3$	$0.10z^{5}$	$0.20z^{5}$	$0.00z^{5}$
$T1_0$	$1.00z^{150}$	$1.00z^{150}$	$0.50z^{150}$		GO_0	$0.10z^{0}$	$0.15z^{0}$	$0.80z^{0}$
$T1_1$	$0.90z^{5}$	$0.90z^{5}$	$0.50z^{5}$		GO_1	$0.30z^{0}$	$0.40z^{0}$	$0.90z^{0}$
$T1_2$	$0.20z^{5}$	$0.20z^{5}$	$0.20z^{5}$		GO_2	$0.55z^{0}$	$0.60z^{0}$	$0.95z^{0}$
$T1_3$	$0.00z^{5}$	$0.00z^{5}$	$0.00z^{5}$		GO_3	$0.55z^{0}$	$0.60z^{0}$	$0.95z^{0}$
$D2_0$	$1.00z^{30}$	$1.00z^{30}$	$1.00z^{45}$					
$D2_1$	$0.00z^{0}$	$0.00z^{0}$	$0.30z^{10}$					
$D2_2$	$0.00z^{0}$	$0.00z^{0}$	$0.10z^{10}$					
$D2_3$	$0.00z^{0}$	$0.00z^{0}$	$0.00z^{0}$					

For each of the process alternatives A, B and C, probabilities and lead times have been assigned for each branch. Probabilities have been assessed through multiple interviews with six persons at Volvo Aero including project leaders, design engineers, simulation experts and test engineers at VAC who are, or have been, involved in the development project studied. Lead-time data have been taken directly from the project documentation and have been scaled for proprietary reasons.

3.3 SFG results

The expected lead-time for go-ahead decision can be derived from the SFG model. Figures 9a and 9b show the cumulative probability of completing the two-phase development stage.

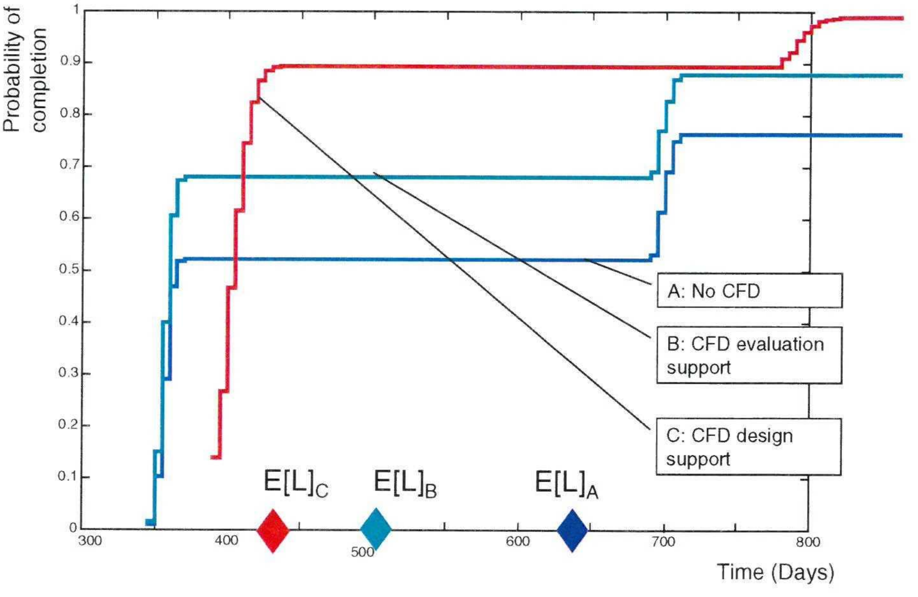

FIG. 9 a. Cumulative probability of expected lead-time ranging over two design phases

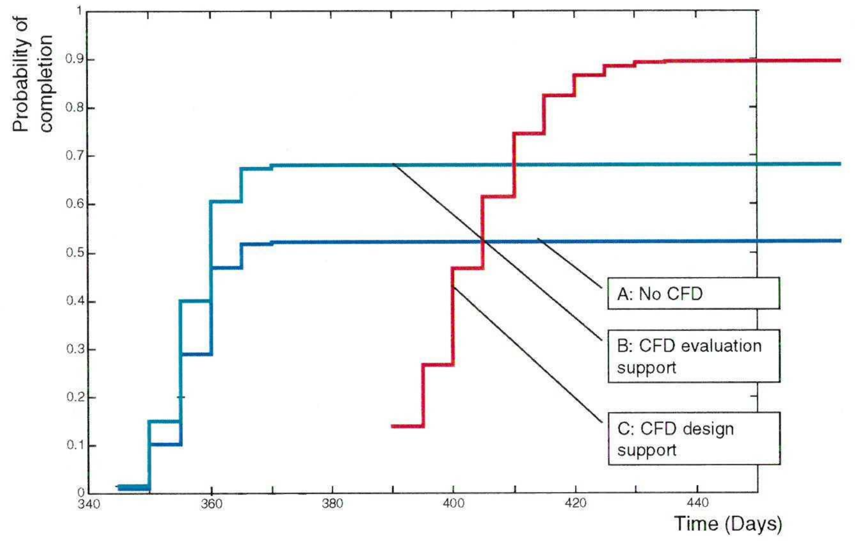

FIG. 9b. Focused time scale

Using CFD support increases the probability of stage completion without redesign from 52% without CFD support to 68% using CFD to support test evaluations, and to 89% using CFD in design. The time penalty of the extra work using CFD is seen if the resolution of the time scale is narrowed as shown in figure 9b. The first stage is completed in between 345 to 375 days for case A and B while case C's first stage is completed in between 390 and 450 days.

The mean value for the expected lead-time is 642 days for case A, 501 days for case B and 435 days for case C. The lead time for a minimum of 80% probability of stage completion is more than 1000 days for case A, close to 700 days for case B and 415 days for case C.

3.4 Evaluation

Depending on how VAC chooses to define the evaluation criteria, different design processes might be selected. In spite of the extra effort added in the initial design stages, the mean expected lead time is 15% shorter for alternative C compared to case B. It is notable that mean lead times for both case A and case B are on a 'probability plateau' indicating that the mean lead times are not among the possible lead times.

If completion probabilities lower than 68% can be acceptable, case B has the shortest expected lead time, followed by case C, and then case A. If as low as 52 % completion probability can be accepted, even case A has a shorter lead time than case C. However, these "possibly faster" processes involve high lead-time variance; the slow rise of the right-hand tails of their cumulative probability graphs represents the likelihood of schedule slippage. More pragmatically, for a minimum 80% probability of stage completion, case C is the obvious option, as the 80% lead times for cases A and B are 241% and 167% respectively of the case C 80% lead time.

4. Discussion

In this paper, SFG modelling and simulation have been used to analyse alternative design processes. This technique has been used to predict the lead time to completion, taking into account the uncertainties in each activity. Based on the analytical results, the design process options can be readily compared in terms of lead time to completion.

However, there are other important development process metrics to be considered, such as cost, quality and flexibility. Since the SFG analysis is based on uncertainties in each activity, the resulting completion profile makes explicit the reliability of process timing, which is one dimension of process quality. (This is sometimes called schedule risk.) This model can potentially be extended to include activity costs [11] and resource constraints [8], but these have not been the topic of this paper. Using this method gives managers and engineers confidence to adopt new engineering processes more quickly, and thus contributes to a more flexible product development process.

In using this modelling method, it is important to keep in mind the underlying assumptions and limitations of such a technique. The SFG model is an abstraction of a real process, and the analytical predictions are based solely upon the model, not the real situation. The fidelity of these predictions depends to a large extent on how well the model itself represents the situation under study. Parameter uncertainties also affect the accuracy of the results. In our application, some activity timing data used to create the model could be obtained from project records; however, the probabilities had to be estimated by specialists based upon their personal project experiences. To validate our modelling results, managers at VAC are collecting data from current projects for comparison with the timing distributions predicted.

While in this paper we have discussed how to compare and evaluate different product development strategies, it is also possible to approach the inverse problem — to prescribe the necessary performance requirements of new design activities. An insight of the following form could be extremely valuable: "We should only adopt this new rapid prototyping method if it reduces the need for confirming experiments by 20% or more." Of course, the introduction of new design activities may in turn affect the timing and success probabilities of other, already existing, design activities. Modelling these secondary effects is essential to assess the overall impact of a proposed change upon the entire development process.

Certainly important insights are to be gained through the interpretation of the SFG analysis to compare different strategies. However, our experience also shows that even the initial process modelling and data gathering activities do stimulate discussion within the organisation leading to engineering design process improvement.

5. Conclusions

In this paper, we have presented an approach to compare alternative product development strategies with respect to their impact on lead time and project success probability. We argue that the SFG methodology, in spite of the difficulties in generating the appropriate model and obtaining the parameter data, is an efficient method to analyse effects of alternative design strategies on the product development process. An industrial case example illustrates the effect of CFD support activities on project completion time and on the risk of project slippage (due to unplanned design iterations).

We found that the process modelling and analysis also led to managerial insight regarding product development process improvement. This insight can be used for understanding the company's development process and to discuss the effect of reducing weak links in the process. These results provided a powerful way of explaining the development process at many levels in the organisation. The method and results were discussed among engineers as well as at senior management meetings.

We recommend the use of SFG as a tool for predicting lead time and project success probability. The method is particularly helpful to compare alternative suggested product development processes and to quantitatively predict the effects of proposed changes to an established process.

6. Acknowledgement

We sincerely appreciate the time and assistance provided by the engineers and managers at Volvo Aero Corporation. Financial support for this research was provided by the Swedish Strategic Foundation's national program ENDREA (Engineering Design Research and Education Agenda) and by MIT's Center for Innovation in Product Development (CIPD).

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Paper G

Computationally Supported Assessment
of Welding Distortions

To be published

Computationally Supported Assessment of Welding Distortions

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SUMMARY A method to improve computationally supported assessment of welding manufacturing is presented. Competitive requirements on cost and reduced lead time forces manufacturing companies to become more efficient. One way of increasing the efficiency is to plan and tune the manufacturing set up so that fewer initial attempts have to be made when starting the manufacturing of a new component. In welding applications, deformations introduced during the welding operation have to be mastered. The production set-up procedure includes design of fixtures, choice of weld orders and welding parameters which all affect both the total manufacturing lead time and the quality of the welded component.

Computational methods to predict the residual stresses and deformations that appear during welding have been developed for some time, but the highly non-linear phenomena still challenges the current research in this field. The complexity of such analyses has limited the number of industrial applications. Welding simulations have so far mostly been performed by researchers in the field.

In this paper a generic computational support process is used to identify and develop critical activities in the computational simulation process based on analysis of an industrial application. The method suggested is based on reduction of the simulation process to a degree allowing iterative elementary case simulations within a limited time frame. Results from the elementary case studies are presented in a so-called welding response matrix (WRM). The resulting trends from the WRM are used to predict the behaviour of more complex geometry's for which simulations also have been conducted. It is demonstrated how this method can be used to improve the use of computational support when assessing distortions by simplifying the most critical activity (which in this case is the mechanical simulation).

Using a structured approach to describe the mechanical welding simulation process also enables communication between computational engineers and production engineers.

1. Introduction

Welding is often used when manufacturing aerospace engine components and causes distortions during the manufacturing process and leaves residual deformations and stresses. These distortions and stresses cause problems both from a production point of view and from a designer's point of view. From a production point of view, the planning, adjusting and optimisation of the manufacturing operation is often critically dependent on the deformation behaviour and residual stresses. Predictions of deformations are frequently based on experience, physical experiments and empirical correlation.

Commonly, input to setting up a new welding manufacturing operation are

- Experience from manufacturing of other components,
- Requirements on process and detail (critical operations)

By simulating the welding operation with numerical methods, such as the Finite Element Method (FEM) [1], new opportunities appear. Idealised numerical experiments, in contrary to physical experiments can be performed iteratively and to a relatively low cost. Phenomena can be isolated and studied analytically. The evolution of parameters over time is just one example of results that can be studied using Finite Element Analysis (FEA).

In this paper, the process of computational welding simulation support is investigated with the objective to find an approach to computational supported assessment of welding distortions. Residual stresses and their post-manufacturing consequences are not studied, albeit their importance. By studying the FE analysis process it is argued that simplifications can systematically be introduced. To illustrate the use of the method a simplified computational support method is defined and applied onto a realistic example - the welding of quadrilateral pipes used in a spacecraft engine exhaust nozzle.

To be beneficial in a production situation the following aspects have to be met

- Reduce lead time and cost of process planning, set-up and operation
- Improve the understanding of the manufacturing by using analytical, computational simulation tools
- Improve communication and experimental learning in a working group, especially between computational specialists and production engineers.
- Increase the (quality) reliability of the weld

1.1 Computational techniques and limitations

The computational complexity and consequently the limitations in problem size have so far limited a wide spread industrial use of these techniques. The limitations originate partly from the number of different *physical processes* involved in welding, and partly from the *computational effort required* to compute these phenomena.

Physical processes to be modelled include plasma interaction and electromagnetic behaviours in the fuze, fluid flow in the weld pool, liquid to solid transformation characteristics, microstructure evolution during temperature changes and mechanical response at high temperatures [3,4]. These physical processes have so far been studied as separate disciplines and assumptions about the other processes have to be made for each separate analysis. It should be mentioned that encouraging results have been found for each separate area. Some of the latest results in welding research can be found in [10].

The *computational effort required* is extensive due to the highly non-linear phenomena that have to be modelled. Material is deformed and joined which requires the computational model to be modified during the simulation; large differences in stiffness within the object cause numerical problems; faces of the object may come in contact and the geometry size itself is problematic. Non-linear FEA is required for welding simulation, see e.g. [2].

Research and development of welding simulations have been tightly coupled to experimental testing and verification. Most methods are experimentally validated on simple geometry, such as plates and cylinders.

In an industrial situation the geometric problem cannot be avoided. Deformations of the entire structure due to the (local) welding operation must be analysed for fixturing etc. Deformations also affect the operational function of the component. Consequently, the geometrical problem size is given higher priority in the industrial situation than in the development of simulation methods.

The approach in this paper is that *reduced quantitative predictability can be accepted in an industrial situation provided that qualitative comparisons between alternatives can be made.* Smaller problem size enables iterative and parametric studies. There is an opportunity to develop methods with acceptable predictable features *if* contribution to productivity can be proven. Another effort to support welding manufacturing is a knowledge-based approach being developed at Sandia Labs [7]. Successful approaches to reducing the lead time for computationally support in manufacturing have also been presented [9]

1.2 A generic computational support process

The problem solving technique using computational methods can be expressed in generic terms if information related to the specific methods, tools and the information situation are clearly separated. There are a number of steps common to this process that have to be performed.

A Generic Computational Support Process, GCSP, is described in figure 1 [5], where situation dependent information (data and methods) are separated from the generic activites.

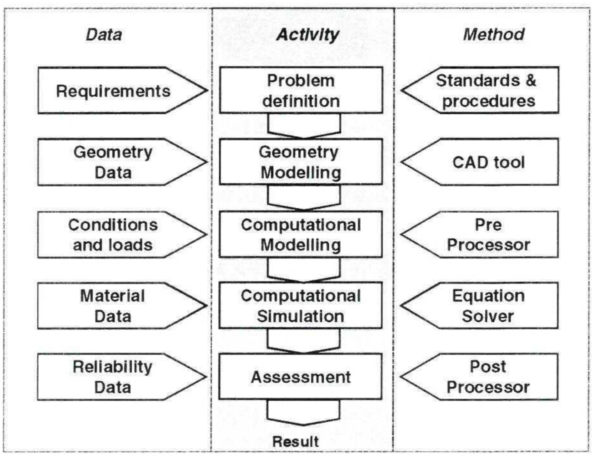

Figure 1: A Generic Computational Support Process, GCSP [5]

These five steps must be conducted to perform a computational simulation of a structure. After the *Problem definition* a *Geometry model* is needed as a basis for a *Computational model*. After the computational model is defined then the *Computational simulation* is performed and finally, an *Assessment* of the simulation results must be made. Each of these activities must be performed in succession, although iterations may occur. These iterations are, however, situation dependent and are therefore left out in the generic description.

Computational processes typically differ within the activities, in terms of lead time consumption and accuracy (quality). The problem definition activity addresses how to identify an appropriate analysis strategy and is most important when facing a new design situation where the most difficult task is to specify which problem to address. For other computational problems, the problem definition is straight forward whereas the geometry modelling and reduction is the major problem, A third situation is where the major problem is the Computational Simulation activity itself. Most non-linear analyses require advanced solution methods, for example.

Computational modelling activities, involving derivation of boundary conditions and discretisation of the geometrical model is often a critical step for aero engine components. Sometimes, the major obstacle is the computational capability and access to material data. This is typically the case when modelling and simulating physical phenomena involving non-linear responses.

Consequently, the GCSP can be specified one step further to suit a specific class of computational problems. Advanced simulation of welding manufacturing is one such area.

2. A generic process for welding simulations

The generic computational support process can be applied to the welding simulation process used to predict mechanical distortion. This process can be seen as a sub set of the GCSP. Since welding simulation always includes simulation of the thermal and mechanical behaviour, these have been separated in the generic description. See figure 2.

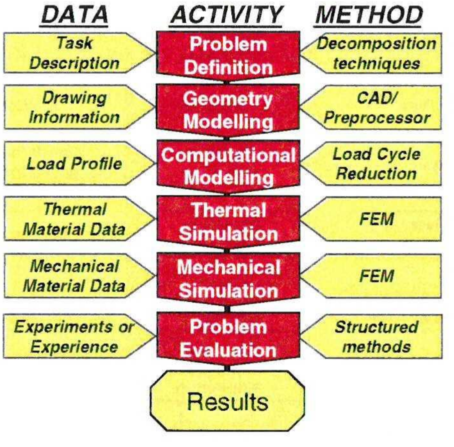

Figure 2: A generic simulation process for welding problems.

2.1 *Analysis of a computational support approach*

Suppose that the component to be welded is geometrically complex and involves several different successive manufacturing operations, including one or several welding operations. It is regarded that a trial and error approach to find acceptable welding process parameters and fixtures would require several costly iterations. To successfully support the choice of process parameters and fixtures we suggest the process parameters to be virtually iterated using computational simulation of the welding operation. This would save both valuable time and money.

After the problem definition, the geometry is simplified as much as possible without loosing the characteristic features of the component. This might seem like a tremendous task, but significant efforts have been made and useful results have been achieved [6]. Due to the highly non-linear computations required to simulate the welding process, stronger limitations in geometric model size are required than for linear analysis of structures. Often, the problem can be reduced to two dimensions. Large geometrical simplifications, on the other hand, typically lead to problems when assigning boundary conditions. The thermal evolution, simulated using FEM, causes large thermal strains and deformations which are simulated in the *mechanical simulation* activity. The mechanical analysis often includes both geometrical non-linearity (definition of new geometry and contacts) and material non-linearity (melting, phase transformation etc). Finally, if there is no experimental support, the quantitative results contain a relatively large amount of uncertainty, which requires a cumbersome process of iterations to assess the validity of the results. In figure 3, the relative effort for each activity in the GCSP for welding simulating of a full 3D representation (Level 1) of an aero engine component (too expensive) and for a reduced geometry description approach (Level 2) is illustrated.

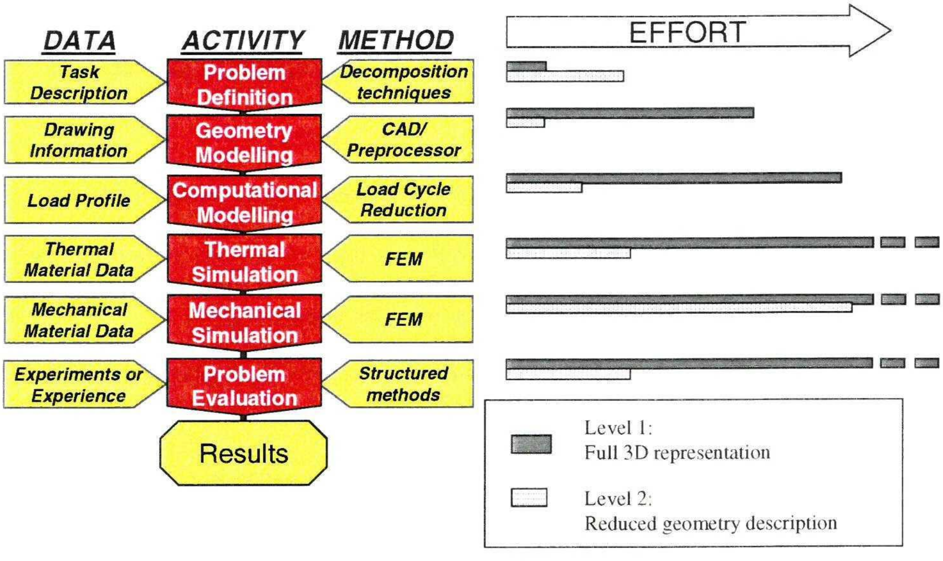

Figure 3: Typical distribution of effort for each activity for a complex aerospace component

Figure 3 illustrates that by carefully defining the problem the geometry model can be reduced. The subsequent activities become manageable and the process can be completed.

However, the still single most cumbersome activity in the geometrically simplified approach is the mechanical simulation activity that limits the problem size. Further reductions are likely to reduce the scope of quantitatively predicting the mechanical behaviour (deformations and stresses). Requirements on a further reduced approach are given in table I.

Table I: Requirements on simulation supported assessment of welding

Requirement	Consequence
Problem size	Geometrically complex structures including welding operations must be possible to analyse
Analysis lead time	Analysis lead times must support operational production work and results have to be provided within the order of days from the assignment.
Enable comparisons	Simplified (comparative) analyses are beneficial only if several alternatives can be studied. Parameter studies must be enabled, to tune the manufacturing parameters numerically.
Verified results	Careful analysis and experimental work must continuously verify a simplified (reduced) approach.

2.2 Elementary case simulations

The approach is to further simplify the computational process with an initial simulation study on an elementary case level, 'Level 3' in figure 4. The results are gathered in a matrix called the Welding Response Matrix (WRM). The WRM is used to identify promising process parameters. These parameters are used to define a larger simulation model or an experimental test on 'Level 2'. Such an approach will reduce the complexity of the computational simulations to a level enabling parameter studies to be made within a limited time frame. The question that arises is weather or not the results are accurate and appropriate enough to support the mechanical assessment activity. The relative effort for each activity is compared for the three levels in figure 4.

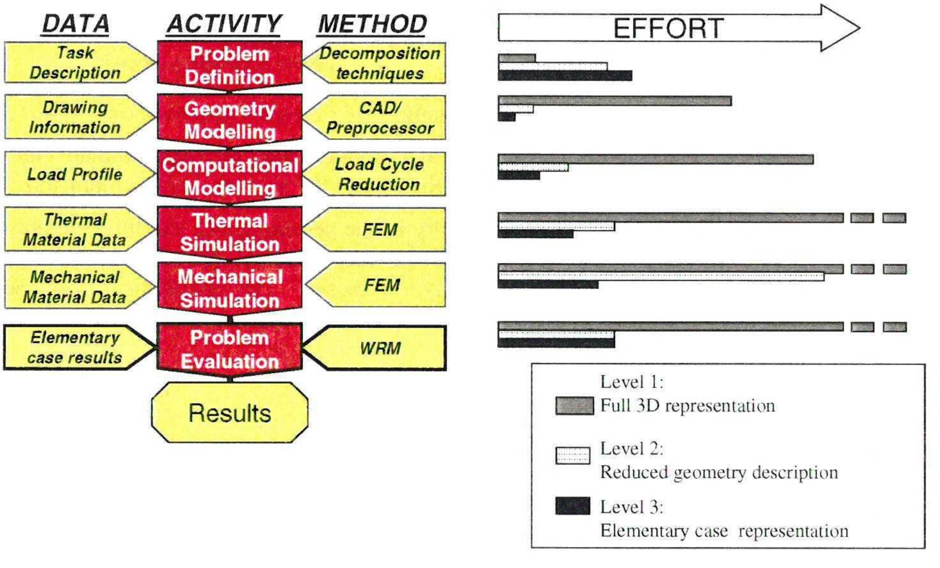

Figure 4: Introduction of a third level, with elementary case representation of geometry.

2.3 Welding Response Matrix

The problem size is reduced to a set of elementary cases, based on a plate geometry as shown in figure 6. Each case is simulated and deformations are displayed as a function of time. A number of characteristic measures are defined. One set of results is normalised and the distortions from the other case simulations are displayed relatively to the normalised, reference case. The reference case and the relative deformations to the other cases are displayed in the Welding Response Matrix, WRM.

In this paper, the differences between the elementary cases are weld geometry and mechanical boundary conditions as defined later.

From analysing the WRM the most promising combination of weld geometry and mechanical boundary condition can be identified. This relative information can be used when setting up a weld experiment or when defining higher level of geometry representation. In this example, a welding simulation of two pipes represents 'Level 2'.

Executing the second level test or simulation is at least a 'best guess', and how accurate this guess is depends on how well the elementary case conditions can be mapped onto a more complex situation. By simulating or testing the more complex situation, with boundary conditions and weld geometry corresponding to the reference elementary case, a second set of results on the second level can be computed. By normalising this second set of results and calculating the relative difference to the 'best guess' results, the quality of mapping between the elementary level and pipe level can now be assessed.

2.4 Definitions of the elementary cases for 'Level 3'

The approach suggested is to further simplify the geometrical complexity for the elementary case to the level of a plate. This enables process parameters to be varied many times since a simple geometrical problem can be simulated using relatively little computational power. Still, the manufacturing problem concerns complex geometry why this complex mechanical situation must be accounted for in some other way.

Welding manufacturing causes deformations and residual stresses due to (primarily) the thermal energy added in combination with the thermal and mechanical restraints. The thermal energy is added locally and the temperature field evolution does not depend on the mechanical boundary conditions. The thermal behaviour has a more local behaviour than the mechanical behaviour.

The same temperature behaviour can give rise to completely different stresses depending on mechanical restraints.

A simplified approach to model the effect of welding process parameters must consider the large mechanical situation, and thus consider different mechanical restraints. In the suggested approach, variations in process parameters and thermal conditions are compared for three different mechanical restraints for the same, simplified, geometry. The three mechanical restraint cases simulated are shown in figure 5.

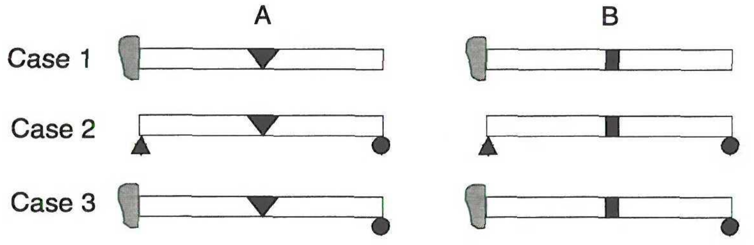

Figure 5: Three different mechanical boundary conditions and two different weld geometries.

Two different weld path cross sections are shown, illustrating two different weld methods. A represents the weld geometry that can be expected when using TIG welding, whereas B corresponds to the weld cross section that can be achieved using electron beam welding or laser welding. Only distortions are considered in this article and for optimisation of e.g. weldability, weld shape or subsequent performance analysis other parameters might have been a better choice. Simulation of distortion requires in itself a number of assumptions to be made. Below a short description of the assumptions that have been made for these analyses follows.

Table II: Assumptions and implications made for the elementary case studies

Assumption	Implication
2D Cross section	Assumes infinite welding speed.
Generalised plane deformation	Used to obtain information of the out of plane behaviour.
Linear elasto-plastic continuum	No creep at elevated temperatures accounted for
Prescribed heat input	Uniformly distributed effect on an defined area
No phase transformations	Good assumption, since the material modelled is a Ni-based supermodel that does not undergo any phase transformations in the solid state.

The geometry of the cross section used for analysis is given in figure 6. The sampling points are placed at a distance *d* from the centre of the weld. The requirement on *d* is that it should be able to trace the difference in the thermal wave propagating horizontally in the plate. The points are also placed outside the melted zone since this is believed to simplify the interpretation of the results. The material properties used in the model are all temperature dependent material data.

The size of the weld area is defined as a constant area for each weld case where the B method represent penetration of the full thickness with vertical borders of the zone of heat input. The A method penetration is described by a triangular shape of heat input as shown in figure 5 and 6. The welding parameters used in the analysis correspond to heat input of 1100 W and an efficiency of 73%. The welding speed was 2200 mm/min. These values were provided by VAC.

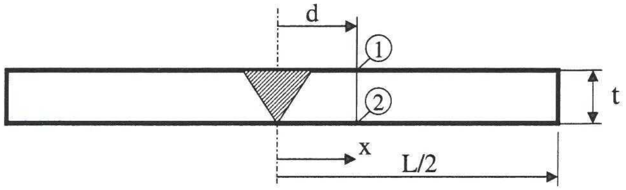

Figure 6: Plate geometry and nomenclature

The elementary case study was performed on a plate having L=20mm, d=2mm and t=2 mm.

2.5 *Analysis of elementary cases*

The analysis of each elementary case results in quantitative transient measures of deformation. The deformation modes are illustrated in figure 7. The use of generalised plane deformation gives the possibility to obtain information about the out of plane behaviour. The model gives the out of plane strain, ε_0 and the curvature, κ, in y and x direction respectively. The total out of plane strain is then written as $\varepsilon_z=\varepsilon_0+\kappa_x*x+\kappa_y*y$. This out of plane correction has previously been used in welding simulations [8].

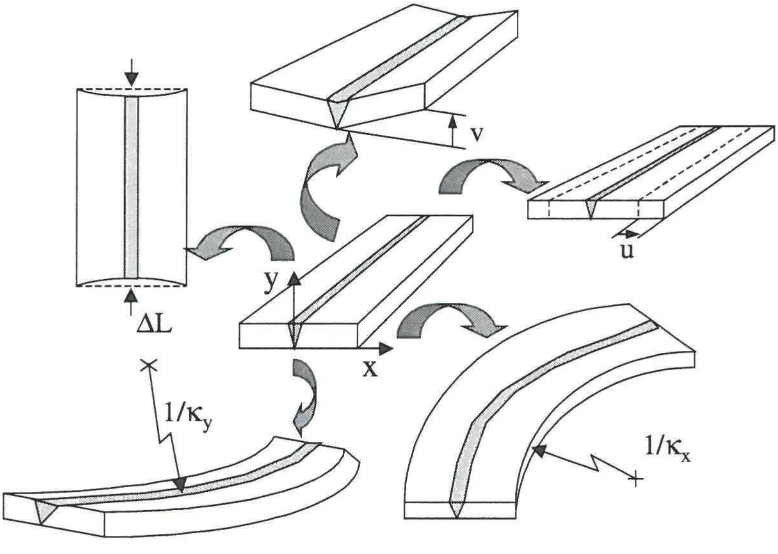

Figure 7: Deformation modes considered for the welded plate.

The plate has five deformation modes. The ΔL can be derived from ε_0, which is the constant out of plane strain.

For each of the mechanical restraint cases the transient deformations are plotted (figures 8-11) together with the temperature difference between point 1 and 2, which are shown in figure 6.

The difference between u_1 and u_2 for case A is caused by the temperature difference ΔT and will make the plate bend downwards. This is in correlation with the v_1 and v_2 deformation. Method B gives no temperature difference between point 1 and 2 and no deformation in the y direction is therefor created. It can also be seen that the constant out of plane deformation is equal in both method A and B. The deformations in case 2 shows a "Butterfly" like behaviour. Again it is believed that the difference between u_1 and u_2 created by ΔT is the driving force for this deformation mode. Case 3 shows a butterfly like deformation mode but with smaller amplitude. This is an effect of the strong mechanical restraint at the left side of the plate.

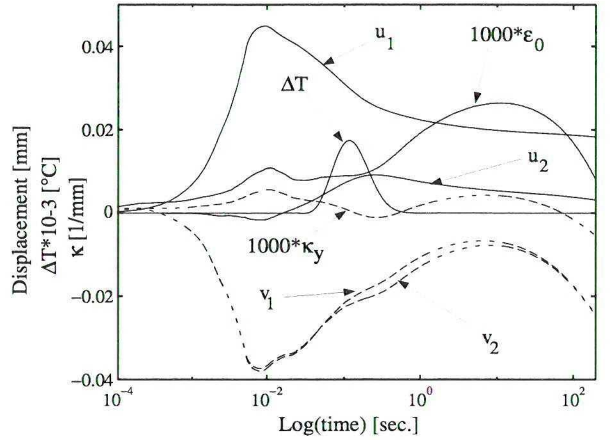

Figure 8: Evolution of the deformation modes during welding and cooling for Case 1A

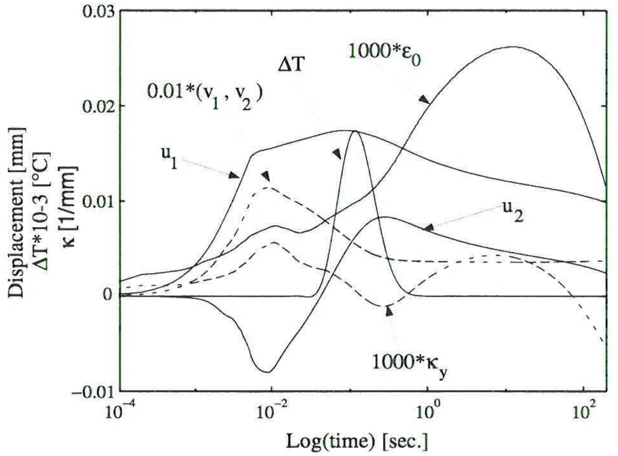

Figure 9: Evolution of the deformation modes during welding and cooling for Case 2A

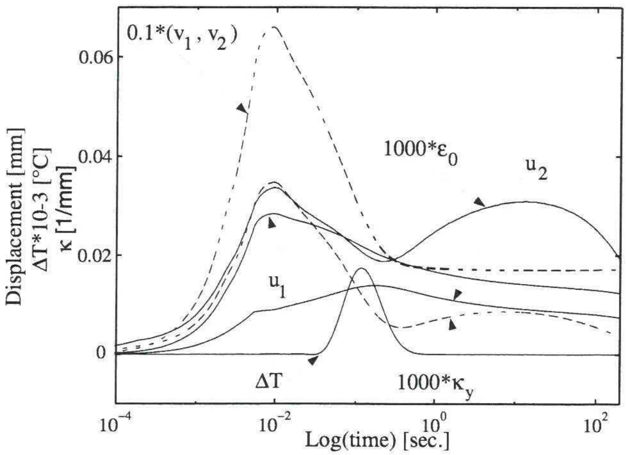

Figure 10: Evolution of the deformation modes during welding and cooling for Case 3A

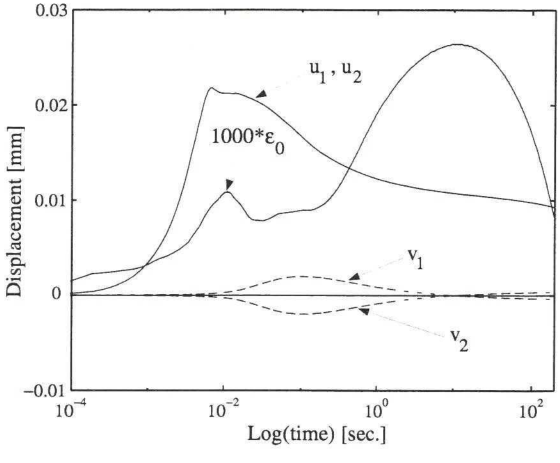

Figure 11: Evolution of the deformation modes during welding and cooling for Case 1 B (and Case 2B and 3B, since these are almost identical).

All three cases show a deformation peak of the u and v values at the start of the welding. The mechanical response is almost immediate while the thermal wave takes some time to reach the sampling points. All cases also show a small influence of the κ_y deformation mode. This is caused by the fact that the heat input is close to symmetric around the x-axis. A stronger effect on this deformation mode would be achieved if the plate were only partly heated at the top of the plate. For all cases the κ_x is approximately zero due to the symmetric positioning around the y-axis.

2.6 *Interpretation of results*

To simplify interpretation of the results and enable a direct comparison of the effect of process parameter changes, a number of key distortions are presented in the Welding Response Matrix. Eleven deformation measures are compared for the six combinations of analyses and expressed as relative measures (% change) to the first restraint case, with the A method, see table III.

Table III: A Welding Response Matrix showing the effect on distortion modes for 6 cases

	Method A			Method B		
	Case 1 (Reference)	Case 2 (% change)	Case 3 (% change)	Case 1 (% change)	Case 2 (% change)	Case 3 (% change)
$u1_{max}$	1	-61	-37	-51	-51	-52
$u2_{max}$	1	-9	53	139	139	136
$v1_{max}$	1	-3109	-1841	-105	-105	-103
$v2_{max}$	1	-3110	-1842	-95	-95	-97
$u1_{res}$	1	-46	-32	-49	-49	-45
$u2_{res}$	1	-73	-18	2	2	10
$v1_{res}$	1	-1623	-803	-99	-99	-100
$v2_{res}$	1	-1613	-798	-101	-101	-100
ε_0	1	-1	28	-18	-18	-18
κ_x	-	-	-	-	-	-
κ_y	1	0	519	-100	-100	-100

2.7 *Simulation of a model at 'Level 2'*

Using the results of the comparative study presented in the WRM in table III, another geometry is defined and analysed. Two simulations are made on the welding of two quadrilateral pipes shown in figure 12. The geometry level now represents 'Level 2' in figure 4. The first simulation is made on a reference case, corresponding to the reference case in the WRM. The second simulation is made based on the most promising combination of restraints and weld geometry given in the WRM, which is using method B and restraint case number 3.

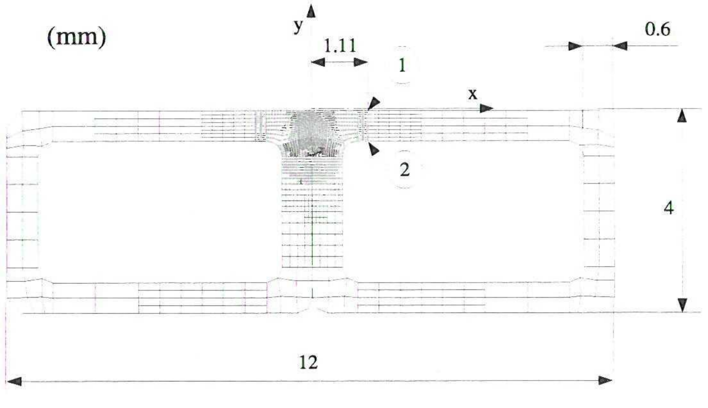

Figure 12: Two welded quadrilateral pipes, welded together

Quantitative transient deformation results of the improved pipe geometry simulation are shown in figure 13 and 14. The measures differ in order of magnitude, as expected, but the deformation profile experience the same transient behaviour of *u* and *v* deformations as was found in the elementary case study.

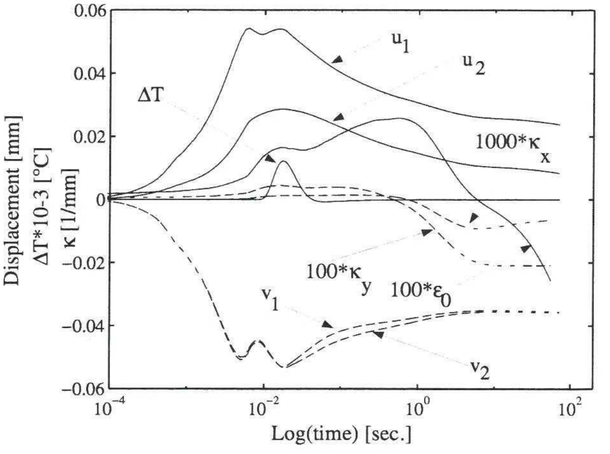

Figure 13: Evolution of the deformation modes during welding and cooling of the pipes with a restraint set equal to Case 1.

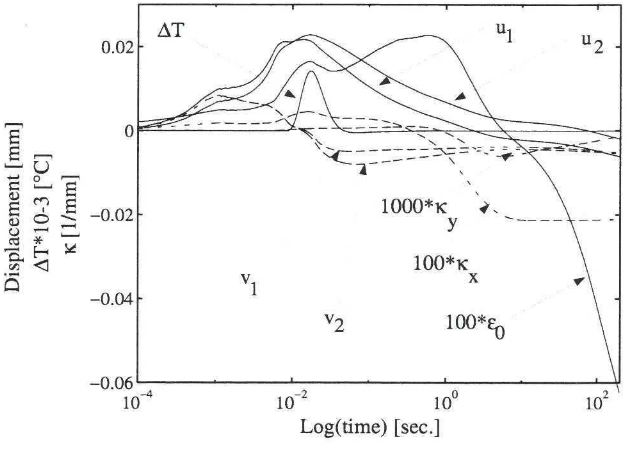

Figure 14: Evolution of the deformation modes during welding and cooling of the pipes with a restraint set equal to Case 3.

The relative comparison between the 'Level 2' simulation and the elementary case level is presented in table IV.

Table IV: Comparison between case 3B deformation and achieved reduction in the pipe case:

Deformation mode	Case reduction %	Pipe reduction %
$u1_{max}$	-52	-60
$u2_{max}$	+136	-21
$v1_{max}$	-103	-116
$v2_{max}$	-97	-116
$u1_{res}$	-45	-126
$u2_{res}$	+10	-123
$v1_{res}$	-100	-85
$v2_{res}$	-100	-85
ε_0	-18	141
κ_x	-	-34
κ_y	-100	2

In table IV, the distortions predicted at the elementary level shows a relatively large difference in magnitude, whereas the trend shows good agreement. The difference in $u2_{max}$ has a likely explanation in that no contact restraints in the gap between the two pipes were included in the model. The surfaces are thus allowed to penetrate each other in the reference case. This penetration does not occur when the boundary conditions of case 3 are used. The relation between the net heat input and the total cross section area is changed between the 'Level 1' and the 'Level 2' simulation. This might explain the difference in for instance ε_0.

Obviously, to increase confidence in the numerical results, several more simulations have to be made. In this report we have emphasised the methodology of identification and simplification of the simulation process. This has enabled iterative simulations to be made with a short total lead time.

3. Conclusion and discussion

In this paper, a generic computational support process (GCSP) model has been applied to advanced Finite Element simulations of the welding manufacturing process.

By analysing the welding simulation process using the GCSP, a number of advantages have been identified;

- The method enables structured analysis of e.g. weaknesses in the simulation process
- Advanced simulation issues can be communicated with other domain specialists, e.g. manufacturing engineers and materials engineers.

To illustrate how the GCSP can be used, a highly simplified approach to analyse welding manufacturing problems using computational support was presented. By releasing the requirement of quantitative predictions, trend analyses have been made on elementary case level. This enabled an iterative study to be made, where different process parameters and restraint sets were analysed. The results were expressed as relative differences of distortion modes and gathered in a matrix, here called WRM - Welding Response Matrix.

Advantages using the WRM are primarily;

- Provides a method to gather and compare simulation results
- Enables comparison between elementary cases
- Several different parameters can be analysed, and the best parameter set can be identified
- Experiments and analysis data can be compared on a structured manner. The WRM can serve as a test bench.
- Also, from a simulation point of view, the effect of different improvements in the computational method can be examined.
- The WRM can be increased with new sets of elementary cases corresponding to other boundary or initial conditions.

To some extent, the results can be used to guide the manufacturing set up of more complex geometries. This guidance was illustrated by investigating the relative distortion between the 'Level 3' and the 'Level 2' simulation (more complex geometry) for conditions identified in the WRM and applied on a 'real case'. Obviously, there are several concerns and limitations with a highly simplified approach.

- Welding manufacturing is a highly non-linear phenomenon to describe and compute.
- Geometric conditions have a strong effect on results. Geometric simplifications are dangerous, and must be validated by experiments
- Boundary conditions (thermal and mechanical restraints) also heavily depend on the process set up and on the real, physical geometry. Again, simplified approaches are limited in scope.

Finally, using a structured generic approach to describe complex simulation problems opens up new possibilities. Major advantages are the structuring and communication of complex (specialist) knowledge. The other is a way to gather experience, such as using the WRM. Also, despite the accuracy of the results from the elementary case simulations, the WRM provides a more structured approach to conduct physical and numerical welding experiments.

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