THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Uncertainty and Robustness in Aerospace Structures

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

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By Anders Forslund

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Doktorsavhandling vid Chalmers Tekniska Högskola.
Series number: 4147
ISBN: 978-91-7597-466-8

Published and distributed by
Division of Product Development
Department of Product and Production Development
Chalmers University of Technology
SE - 412 96 Gothenburg
Sweden

Telephone + 46 (0)31-772 1000
URL: www.chalmers.se

Cover:
Orville Wright piloting the Wright Model A during proving flights for the U.S. Army at Fort Myer, Virginia, in July of 1909. The Wright Brothers' ingenious research approach set a precedent for modern aerospace analysis.

Printed in Sweden by
Chalmers Reproservice
Gothenburg, Sweden, 2016

ABSTRACT

Engineering is not an exact science. In fact, all engineering activity contain some degree of assumption, simplification, idealization, and abstraction. When engineered creations meet reality, every manufactured product behaves differently. This variation can be detrimental to product quality and functionality. In an aerospace context, this variation may even result in serious threats to the safety and reliability of aircraft. However, it is not the variation in and of itself that is harmful, but the effects it imposes on functionality—an important distinction to make.

Reducing *sources* of variation is often associated with tightening tolerances and increasing cost. Instead, it is preferable to eliminate the *effects* of this variation by making designs more robust. This idea is at the core of robust design methodology.

Aerospace is an industry characterized by the complexity of its products and the multidisciplinary nature of its product development. In such contexts, there are significant barriers against implementing uncertainty-based design practices.

The research presented in this thesis aims at identifying the role of robust design in general, and geometry assurance in particular, in the early phases of aerospace component design. Further, this thesis proposes a methodology by which geometry assurance practices may be implemented in this setting. The methodology consists of a modelling approach linked to a multidisciplinary simulation environment.

In a series of case studies, the methodology is tested in an industrial setting. The capability of the methodology is demonstrated through several applications, in which the effects of geometric variation on the aerodynamic, thermal, and structural performance of a load-bearing turbofan component are analysed. Investigated effects include part variation, fixture variation, part configuration and welding.

The proposed methodology overcomes many of the current barriers, making it more feasible to assess geometric variation in the early design phases. Despite some limitations, the methodology contributes to an academic understanding of how to evaluate geometric variation in multidisciplinary simulations and provides a tool for industry. Geometric variation is only one source of uncertainty amongst many others. By evaluating geometric variation against the framework of uncertainty quantification, this thesis addresses the relative importance of geometry assurance against other product development activities.

Keywords: Geometrical variation, geometry assurance, simulation, robust design, uncertainty quantification

ACKNOWLEDGEMENTS

This study has been carried out at the Department of Product and Production Development at Chalmers University of Technology in Gothenburg and at GKN Aerospace in Trollhättan, Sweden.

I would first like to thank my academic supervisor, Professor Rikard Söderberg. Thank you for all your good advice and unwavering support.

Further, I wish to express my deepest gratitude to my industrial supervisor, Dr. Johan Lööf with GKN Aerospace. I am dependent on your dedication and expertise.

I would like to give my warmest thanks to Professor Daniel D. Frey at MIT for taking me under his wing for the better part of a year. On the same note, I also want to thank Professor Kevin Otto at Singapore University of Technology and Design.

I am very grateful to everybody at GKN. Thank you for your warm welcome, your helpfulness and your openness to new ideas. Special thanks to Sören Knuts, Alejandro Vega Galvez and Peter Johansson. I would also like to express my sincere gratitude to Professor Ola Isaksson for taking his time to help me both at Chalmers and GKN.

I would also like to acknowledge the Swedish Agency for Innovation Systems (VINNOVA) and the Swedish National Aeronautics Research Program (NFFP) for their financial support. I would like to thank the ProViking Research School, the Sweden America Foundation, and Chalmersska Forskningsfonden for the scholarships that enabled me to spend a year at MIT.

I also want to acknowledge Gunilla Ramell for her excellent language editing.

Most of all, I want to thank past and present research colleagues at Chalmers. This thesis relies heavily on the contributions of my co-authors Christoffer Levandowski, Julia Madrid and Samuel Lorin. I couldn't have done this without you. Also, thanks to everyone else at PPU for making it such a pleasure to come to work every day.

I would like to express my gratitude towards my sister and colleague, Karin Forslund, who got me here in the first place. I also want to thank my parents, and all family and friends outside work.

Finally, I thank my girlfriend Klara for her unwavering support throughout this seemingly never-ending endeavour. I don't know how I ever managed without you.

Anders Forslund
Gothenburg, July 2016

PUBLICATIONS

Paper A
Forslund, A., Söderberg, R., Isaksson, O. and Lööf, J., (2011), ”Multidisciplinary Robustness Evaluations of Aero Engine Structures”, *Proceedings of International Society of Air-Breathing Engines, ISABE 2011, September 12-16, 2011*, Gothenburg, Sweden

Paper B
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Paper C
Forslund, A., Levandowski, C., Lööf, J. and Söderberg, R., (2012), “Robust Lifecycle Optimization of Turbine Components Using Simulation Platforms”*, Proceedings of 28th Congress of the International Council of the Aeronautical Sciences, ICAS 2012*, September 23-28, 2012, Brisbane, Australia

Paper D
Forslund, A., Madrid, J., Söderberg, R., Lööf, J., Knuts, S., Isaksson, O. and Frey, D. D., (2016), “Bridging the Gap between Point Cloud and CAD: A Method to Assess Form Error in Aero Structures”*, Proceedings of the 18th AIAA Non-Deterministic Approaches Conference, SCITECH 2016*, January 4-8, 2016, San Diego, California, USA

Paper E
Forslund, A., Madrid, J., Lööf, J. and Söderberg, R., (2016), “Robust design of aero engine structures: Transferring form error data when mapping out design spaces for new turbine components”*, Proceeding of the 14th CIRP Conference on Computer Aided Tolerancing, CIRP CAT 2016*, May 18-19, 2016, Gothenburg, Sweden

Paper F
Forslund, A., Madrid, J., Isaksson, O., Lööf, J., Frey, D. D, and Söderberg, R., (2016), ”Evaluating How Functional Performance in Aerospace Components is Affected by Geometric Variation”*, Submitted to: SAE International Journal of Aerospace*

Paper G
Forslund, A., Lorin, S., Madrid, J., Lööf, J., Lindkvist, L., Wärmefjord, K., and Söderberg, R., (2016), ”Fatigue Life Optimization of Welded Aerospace Structures Using Permutation Genetic Algorithms”, Submitted to: *ASME Journal of Computing and Information Science in Engineering*

ADDITIONAL PUBLICATIONS

Levandowski, C., Forslund, A., Johannesson, H. and Söderberg, R., (2012), "Platform Strategies from a PLM Perspective—Theory and Practice for the Aerospace Industry", *Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, *SDM 2012*, April 23-26, 2012, Honolulu, Hawaii, USA

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Lorin, S., Forslund, A., Wärmefjord, K., Lindkvist, L. and Söderberg, R., (2016), "Non-Nominal Welding Simulation of Nominally Identical Parts", Submitted to: *ASME Journal of Computing and Information Science in Engineering*

DISTRIBUTION OF WORK

Paper A
Forslund, Söderberg, Isaksson and Lööf outlined the underlying concept. The case study and simulations were performed by Forslund, with guidance from the other authors. Forslund drafted the paper, while the other authors contributed with their comments and feedback.

Paper B
Forslund outlined the concept with the support of Lööf and Söderberg. The case study and simulations were performed by Forslund, whereas Vega Galvez prepared the simulation input data. Forslund drafted the paper, while the other authors contributed with their comments and feedback.

Paper C
Forslund outlined the concept with the support of the other authors. The case study and simulations were performed by Forslund. Forslund drafted most of the paper, whereas Levandowski wrote the section on Product Lifecycle Management. The remaining authors contributed with their comments and feedback.

Paper D
Forslund outlined the concept with the support of the other authors. Forslund performed the case study and simulations, and drafted the paper. The remaining authors contributed with their comments and feedback.

Paper E
Forslund outlined the concept with the support of the other authors. Forslund performed the case study and simulations. Forslund drafted most of the paper aided by Madrid. Lööf and Söderberg contributed with their comments and feedback.

Paper F
Forslund outlined the concept with the support of the other authors. Forslund and Madrid synthesized the theory. Forslund drafted most of the paper, whereas Madrid drafted the section on Forward Applicability. Isaksson, Lööf, Frey and Söderberg contributed by reviewing the paper.

Paper G
Forslund outlined the concept with the support of the other authors. Lorin performed the welding simulations. Forslund wrote the genetic algorithm. Forslund, Lorin and Madrid drafted the paper. Lööf, Lindkvist, Wärmefjord and Söderberg contributed by reviewing the paper.

TABLE OF CONTENTS

LIST OF ACRONYMS

BC	Boundary Condition
COTS	Commercial Off-The-Shelf
CFD	Computational Fluid Dynamics
CAD	Computer-Aided Design
DfSS	Design for Six Sigma
DRM	Design Research Methodology
FEA	Finite Element Analysis
GA	Genetic Algorithm
IC	Initial Condition
LPT	Low-Pressure Turbine
NURBS	Non-Uniform Rational Basis Spline
PDE	Partial Differential Equation
RQ	Research Question
RSP	Risk-and-revenue Sharing Partner
TRL	Technology Readiness Level
TRS	Turbine Rear Structure

1 INTRODUCTION

This chapter provides a short introduction to the research documented in this thesis, the project goals, the research questions and a brief outline.

1.1 GENERAL INTRODUCTION

Air travel continues to be the fastest growing of all modes of transportation, and although the aircraft themselves are continuously becoming more fuel-efficient, total fuel use and emissions are steadily rising (Lee *et al.* 2001). There is a conflict between growth and environmental impact, which has motivated the aircraft manufacturing and airline industries, the scientific community, and governmental bodies to act to reduce emissions. From an aircraft manufacturer point of view, the best way to contribute is by producing aircraft that are fuel-efficient.

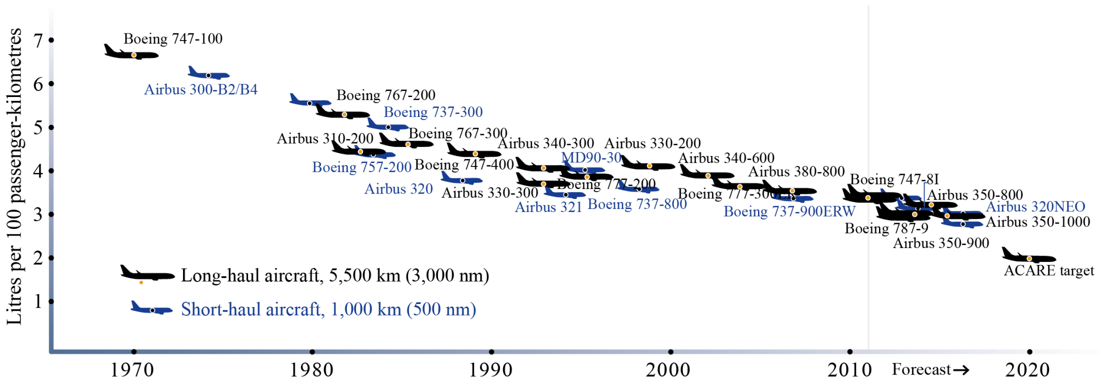

Figure 1: Fuel Consumption 1970-2020.

Source: GKN Aerospace, based on data from IATA (Peeters et al. 2005)

Figure 1 shows how aircraft fuel consumption has decreased over the past forty years. Since the introduction of the first commercial jet airplane, the fuel efficiency of commercial aircraft has doubled. Much of this improvement can be attributed to the introduction of the high-bypass turbofan engine. However, as bypass ratios have increased, engine diameters have also become larger, leading to an increase in engine weight and aerodynamic drag (Lee *et al.* 2001). If engines were made any larger, the drag and weight penalty would outweigh any gains in propulsive efficiency. Therefore, to keep reducing future fuel consumption, other methods of making engines more fuel-efficient must be developed.

One path has been the introduction of high pressure-temperature super-alloys inside the engines, which has allowed for a higher temperature combustion, which in turn improves engine efficiency (Isaksson 1998). The usage of lightweight materials in engine structures, such as composites, has also been used as a means of reducing fuel consumption.

The above improvements are all examples of developments in engine *technology*. A supplemental approach would be to develop better *design methodology*. Improving design tools might enable better engine designs. This thesis examines the use of probabilistic methods as a means of creating more optimized engine designs. Specifically, it looks at implementing robust design methodology to account for geometric variation in engine structures that carry large thermal, structural and aerodynamic loads. If the effects of geometrical variation can be identified and suppressed, the designer would be able to create optimized, lightweight structures without sacrificing quality or increasing costs.

1.2 GEOMETRIC VARIATION AND OTHER UNCERTAINTY

"As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality"
Albert Einstein (1922)

In today's aerospace industry, simulation is increasingly being used to reduce cost and minimize time to market. Unlike physical experiments, where conditions cannot be precisely controlled, simulations are inherently deterministic—the same simulation always yields the same output. However, this does not imply that simulations are more accurate than physical experiments. Rather, the validity of a simulation model is measured only on how accurately it reproduces real-world results (Chen *et al.* 2004).

Deficiencies in simulations can arise from many things. According to Oberkampf *et al.* (2002), such deficiencies may arise from inadequate physical understanding and mathematical modelling of reality. Deficiencies may arise from programming error or a designer's inability to correctly interpret results. The focus of this thesis, however, is the inherent deficiency of simulations in accounting for the geometric variation that stems from an imperfect manufacturing process. In this thesis, the effects of geometric variation and its relation to other sources of uncertainty will be investigated. In dealing with this problem, this thesis uses the theoretical framework found in three overlapping scientific areas: *robust design methodology*, *geometry assurance* and *uncertainty quantification*.

Robust design methodology is an engineering methodology that aims at minimizing the effects of variation without eliminating variation itself. It is often motivated by a desire to increase quality and reduce cost in product development (Chang and Ward 1995, Chang *et al.* 1994). Robust design methodology is based on the notion that all systems have a certain degree of inherent variation and that accepting and assessing this fact may improve product quality without increasing costs (Taguchi *et al.* 2005).

In this thesis, robust design methodology is implemented to address geometric variation in products. A geometrically robust design is defined by Söderberg and Lindkvist (1999) as a design that fulfils its functional requirements and meets its constraints even when the geometry is afflicted with minor manufacturing or operational variation. *Geometry assurance* is a set of activities in the concept, verification and production phase aimed at reducing the effects of geometrical variation and increasing the precision of functional attributes of products (Söderberg, Lindkvist, and Carlson 2006).

Part variation comes from variation in the manufacturing process and wear in manufacturing tools. This variation, together with variation in fixtures and assembly process, lead to geometric variation in the final product. Further, the robustness of the design solution influences how variation will propagate and accumulate. Two of the most important robustness aspects to consider are assembly robustness and part positioning robustness.

For the past few decades, advances in computational capabilities have made computer simulation of physical processes an important tool used in the design of engineering systems (Oberkampf and Trucano 2002, Agarwal *et al.* 2004). In applying principles of robust design methodology and geometry assurance to engineering activities that use these virtual tools, it is important to address modelling and simulation uncertainty.

Uncertainty quantification is the scientific field of quantitative characterization and reduction of uncertainty in applications. This research is commonly motivated as a means of improving reliability in safety-conscious industries, such as the aerospace industry (Kenny and Crespo 2011, Oberkampf *et al.* 2002) and nuclear industry (Oberkampf and Trucano 2008). As computer simulation is a commonly used approach to study problems in uncertainty quantification, a framework has been developed to account for different types of uncertainty. Three different classes of uncertainty have been identified. *Aleatory uncertainty*, also known as *irreducible*, *inherent* or *stochastic* uncertainty or *variability*, is associated with the inherent variation in the physical system or environment under consideration. *Epistemic uncertainty*, also known as *reducible*, *subjective* or *cognitive* uncertainty, can be defined as a potential inaccuracy associated with the deficiency in any phase or activity in the simulation process stemming from *lack of system knowledge*. Finally, an *error* is defined as a *recognizable* inaccuracy in any phase or activity of modelling and simulation that is *not* due to a lack of knowledge. This error can be either *acknowledged* or *unacknowledged*. Acknowledged errors are inaccuracies that are recognized by analysts, whereas unacknowledged errors are inaccuracies that are *not* recognized by analysts.

1.3 PURPOSE AND GOAL OF THE RESEARCH PROJECT

The purpose of the research presented in this thesis is to identify the role of robust design in general, and geometry assurance in particular, in the early phases of aerospace component design. Engineering activities in these early design phases rely heavily on computer simulation. Therefore, one of the goals is to develop a simulation methodology that connects geometry assurance tools with multidisciplinary analysis incorporating computational fluid dynamics and finite element analysis software. The result could then be used to evaluate the aerodynamic, thermal, and structural effects of geometric variation.

The validity of computer simulations as a tool comes from their ability to accurately predict reality. Validating a simulation model can be performed by estimating all its potential uncertainty and error. Geometric variation is only one source of uncertainty amongst many others. By portraying geometric variation against the framework of uncertainty quantification, this thesis also aims at assessing the relative importance of geometry assurance against other product development activities.

1.3.1 Academic and industrial relevance

The research presented in this thesis is characterized by a consideration of both a *research challenge* and an *industrial opportunity*. These two objectives are interconnected, and part of the research challenge is to deliver results that are relevant and applicable to industrial needs. In applied research, a great distance to the object of study and a lack of feedback easily lead to a stultified learning process, which may result in ritual academic blind alleys, in which the effect and usefulness of research becomes unclear and untested (Flyvbjerg 2006). In the application of robust design and geometry assurance techniques to early phases of aerospace component design, a challenge was identified in modelling an engineering system with elements from many disciplines and organisations—a challenge that constitutes a research gap between academia and industry. In comparing the interview study with the literature review, it was concluded that the engineering problems that arise in industry are of a very different scale than those often presented in scientific publications, as academic research generally tries to find theoretically optimal solutions to simplified sample problems. In the work presented in this thesis, the close connection to industry made it possible to create test cases that captured the complexities of real-world product development. These factors contributed to making this research relevant to both industry and academia.

1.4 RESEARCH QUESTIONS

In this project, three research questions have been identified. They are as follows:

Research Question I: **What barriers to implementing geometry assurance practices can be identified in the aero engine industry?**

Despite being widely understood to increase quality and reduce costs and lead times, the industrial implementation of probabilistic design practices in general, and geometry assurance activities in particular, has met with some resistance. This research question aims at identifying the underlying barriers that inhibit a successful implementation of geometry assurance in an aerospace industrial setting.

Research Question II: **How can geometry assurance methods be implemented in multidisciplinary simulations in industrial settings?**

This research question addresses how the effects of geometrical uncertainty stemming from part and assembly variation can be evaluated in a multidisciplinary environment. Part of answering this question lies in overcoming the barriers identified in answering Research Question I.

Research Question III: **What role should geometry assurance play in the early phases of aerospace component design?**

A prerequisite for answering this question is that the effects of geometric variation on product functionality have been adequately quantified. Further, to assess the relevance of geometry assurance, the benefits of performing geometry assurance need to be balanced against the cost, complexity and computational intensity of the methods used. This research question aims at understanding geometric variation in a broader context, i.e. the relative importance of geometry assurance against other product development activities.

1.5 DELIMITATIONS

This research project is a collaborative effort between the Department of Product and Production Development at Chalmers University of Technology and a subsystem supplier in the aerospace industry. The research presented in this thesis is based on this context; however, as with all research, the aim is that the results presented here should be generally applicable to other academic and industrial areas.

The main scientific contribution of this work lies in the field of robust design and quality assurance. However, the work touches on many disciplines, such as finite-element-analysis, computational-fluid dynamics, and product-lifecycle-management. This thesis tries to keep pace with the cutting edge in these individual disciplines, both by reviewing the literature and collaborating with experts in these fields. However, the usage of these technologies serves the sole purpose of supporting the contribution in the field of robust design and quality assurance. It was deemed neither practical nor relevant to approach these individual disciplines with the same scientific rigor as has been applied in approaching the main subject.

1.6 ABOUT THE RESEARCH GROUP

This research was carried out in the "Geometry Assurance and Robust Design" research group of the Wingquist Laboratory at Chalmers University of Technology. The research activity involved in the "Geometry Assurance and Robust Design" group focuses on decreasing the effect of variation through all stages of product realization (as depicted in Figure 2). The focus in this project is on activities in the concept phase.

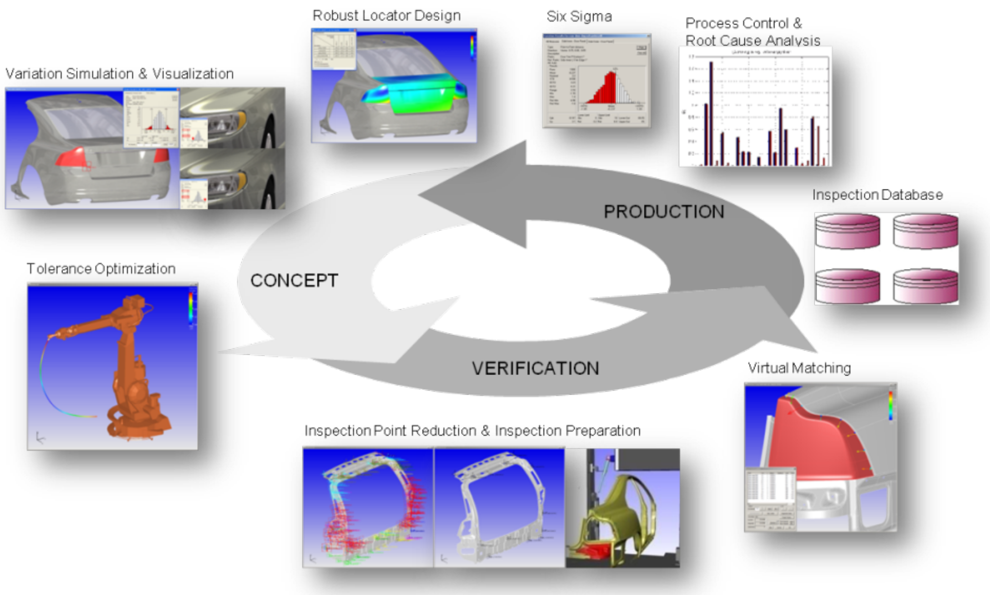

Figure 2: The set of activities involved throughout the product realization process in geometry assurance.

This research project has been financed by Swedish National Aeronautics Research Program (NFFP), a part of the Swedish Agency for Innovation Systems (VINNOVA). The project is also part of the ProViking program, the main focus in which is on industry featuring manufacturing and/or development in Sweden. ProViking is supported by the Swedish Foundation for Strategic Research.

1.7 THESIS STRUCTURE

The following structure has been selected to present the thesis:

- **Chapter 1** provides a general background to the research included in this thesis. The chapter declares the purpose and goal of this project, introduces the research questions and outlines the delimitations of this study.
- **Chapter 2** describes the research methodology implemented and used during this project.
- **Chapter 3** presents the frame of reference—the theoretical and technical background. This chapter places the research in its scientific context.
- **Chapter 4** provides a short summary of the appended papers with a focus on results and discusses the interconnectedness between the results presented.
- **Chapter 5** evaluates how the results achieved answer the research questions. It also provides a discussion of the industrial and scientific relevance of the findings, as well as the verification and validity of the results achieved.
- **Chapter 6** presents the main conclusions to be drawn from this study, and gives some suggestions for future work.
- **Chapter 7** provides a list of references.

2 FRAME OF REFERENCE

This chapter presents the theoretical background and frame of reference that form the foundation for the research presented in this thesis.

The research presented in this thesis touches on many disciplines. First, an introduction is given to the three overlapping scientific areas that deal with assessing variation: *robust design*, *geometry assurance* and *uncertainty quantification*. Additionally, a section is devoted to genetic algorithms. Finally, this chapter provides a brief background to the aerospace industry in addition to a technical introduction to jet engine technology and turbine rear structures.

2.1 ROBUST DESIGN METHODOLOGY−TAGUCHI METHODS

"Without deviation from the norm, progress is not possible"
Frank Zappa (1971)

Robust design is an engineering methodology that aims at minimizing the effects of variation without eliminating the variation itself. It is often motivated by a desire to increase quality and reduce cost in product development and as such, it is related to Lean Product Development (Chang and Ward 1995, Chang *et al.* 1994). Robust design methodology contains both qualitative and quantitative elements (Taguchi *et al.* 2005). From a qualitative standpoint, robust design can be regarded as a design philosophy based on the notion that all systems feature some degree of inherent variation and that accepting and assessing this fact can improve product quality without increasing costs. Robust design methodology also incorporates an array of quantitative methods, most of which are applications of statistical theory.

Robust design methodology has its origins in the post-World War II rehabilitation period in Japan. Japanese industry was suffering heavily from a lack of quality in produced goods. However, the rehabilitation speed was accelerating, and major efforts were made to improve quality in many industrial areas. The telecommunications engineer *Genichi Taguchi* popularized the idea of improving quality by minimizing the effects of variation, rather than eliminating the variation itself. This idea was driven by a need to improve product quality while at the same time reducing costs. These ideas gained a lot of traction in Japan (Nair *et al.* 1992), but it was not until the 1980s that the Taguchi methods were introduced to American academia (Kackar 1985, Chen *et al.* 2004, Nair *et al.* 1992). Since then, several books on the Taguchi methods have been published (Fowlkes 1995, Phadke 1989, Jen 2005). In addition, Taguchi's own books were published in English, where the practices were labelled "quality engineering".

Robust design challenges the notion that all variation needs to be removed in order to obtain a high-quality product. Instead, a system view of a product is adopted, which differentiates between *input* and *output* parameters. Figure 3 shows such a system. The input parameters define the *characteristics* of a system. These are independent and the designer can control their nominal values. The outputs, on the other hand, are parameters that are dependent on the inputs—they can be viewed as a transformation of the input signal. The outputs define the system *properties*, which in turn define the desired functionality of the product.

Figure 3: System view of a product or process.

Taguchi divides the inputs into three categories; he distinguishes between *noise factors*, *signal factors*, *control factors* and output response. The noise factors add some uncertainty to a system. By selecting the appropriate values of the control factors, the noise parameters can be kept from negatively affecting the output response. A common illustration is the P-diagram shown in Figure 4.

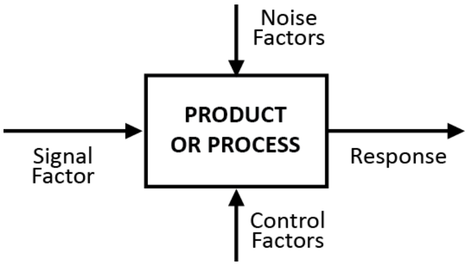

Figure 4: P-diagram, as defined by Phadke (1989).

The distinction between noise factors, signal factors and control factors is not always evident. In real-world applications, noise is present in all parameters. Conversely, in computer simulations, experiments are deterministic which means that all parameters are controllable. In the work presented in this thesis, no distinction has been made between types of parameters.

There are three stages in finding robust designs, namely *concept design*, *parameter design* and *tolerance design* (Phadke 1989).

2.1.1 Concept design

Concept design occurs in early production development phases, during which the designer produces several options that fulfil the intended design. These designs are then evaluated and compared against each other. Andersson (1996) suggests that the design of solution principles that are almost inherently robust has great potential compared to Taguchi's fine-tuning of parameters. Chang *et al.* (1994) define conceptual robustness as robustness against variation on the part of the design performed by other team members and argue that concept decisions are too often made early in the design process based on insufficient data.

2.1.2 Parameter design

The idea behind Taguchi's parameter design is that by selecting a different *value* of an input parameter, the variation in an output parameter can be reduced. Figure 5 illustrates this idea. The input variable on the X-axis has some degree of variation, illustrated by a Gaussian bell curve. This variation translates though the system into an output variation. However, as the function is nonlinear, moving the nominal value of the input variation will reduce the variation in the output parameter.

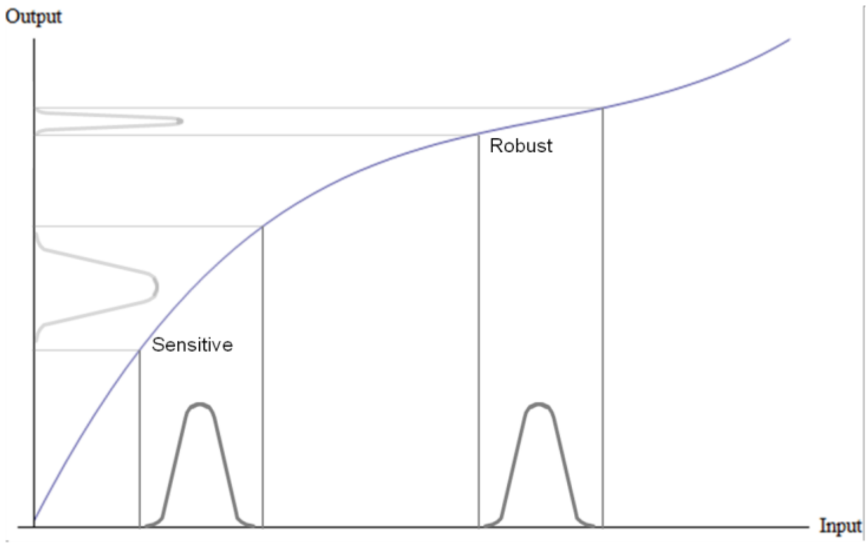

Figure 5: Parameter Design on a one-dimensional system.

The benefit of parameter design is that moving the nominal value usually comes at no additional cost, whereas reducing the variation by tightening tolerances generally leads to a more expensive manufacturing process.

Parameter design plays such a central part of robust design methodology that many view these two terms as synonymous (Wu and Tang 1998, Taguchi *et al.* 2005). In some publications, the terms "robust design" and "parameter design" are used interchangeably (Nair *et al.* 1992). Others look at robust design as a broader concept in which parameter design is one important discipline amongst others (Fowlkes 1995, Park *et al.* 2006, Andersson 1996).

In parameter design, different analysis and optimization techniques are performed to find the optimal settings for the control parameters. In unknown systems with multiple inputs and outputs, there are many different procedures for conducting experiments. This field, called *experimental design* or *design of experiments*, is a field of study in itself. Although Taguchi has made some important contributions to this area, most notably by introducing *orthogonal arrays* (Nair *et al.* 1992), publications by Box and Draper (1959), Michaels (1964) and Morrison (1957), have played an equally significant part. Simpson et al. (2001) conduct a comprehensive review of different experimental design techniques and applications. In the context of experimental design, robust design methodology is often viewed as a subset of *response surface methodology* (Myers and Montgomery 2002, Chen and Lewis 1999).

2.1.3 Tolerance design

In engineering, *tolerances* define the permissible limits of variation in dimensions, properties, etc. In a system, tolerances are defined for inputs as well as outputs. As tighter tolerances imply higher costs, it is preferable to choose *input* tolerances in such a way that manufacturing costs are minimized. At the same time, the *output* parameters should be optimized to ensure product quality. In *tolerance design,* the goal is to allocate input tolerances to optimize the system outputs (Phadke 1989). To enable this outcome, quality has to be transformed into a quantifiable entity. Taguchi relates quality to costs by introducing the notion of *quality loss* as a measure of "the loss imparted by the product to society from the time the product is shipped" (Taguchi *et al.* 2005).

Taguchi argues that deviations from the nominal do affect quality, even when these deviations lie within specified tolerances. Taguchi proposes the use of a *quadratic* loss function to define the relationship between variation and costs, as defined by Equation 1. Figure 6 visualizes this relationship.

$$L(y) = z(y - T)^2. \quad (1)$$

This quality loss is used to measure the financial loss to society resulting from poor quality; it represents costs that are associated with issues like quality branding, repair, and increased assembly time. Further, there is variation of quality loss functions; nominal-the-best, smaller-the-better, larger-the-better, or asymmetric that are applicable to different situations (Phadke 1989).

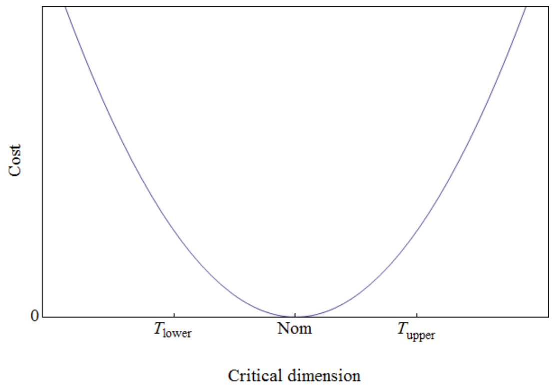

Figure 6: The quadratic quality loss function (Phadke 1989).

How tolerances are applied is a key factor affecting the final variation of products. There are two types of tolerance schemes, the traditional dimensional tolerances where limits are set on the dimensions of parts and products, as opposed to geometrical tolerances where the limits are set on form, orientation, location, runout, profile and symmetry (Jami *et al.* 2008, Lorin 2012).

Tolerances can be applied using a top-down or a bottom-up approach. In the top-down approach, requirements are set on the functions of the assembled product (Lööf 2010, Wärmefjord 2011). These requirements are broken down into requirements on subsystems down to requirements for individual parts. In the bottom-up strategy, on the other hand, tolerances are based on the experience of similar parts or the application of generic tolerances. In both strategies, it is important to be able to predict the accumulations of tolerances from parts and fixtures to realized products. In the top-down strategy, it is important to assure that the broken-down requirements do in fact lead to the applied tolerance. In the bottom-up strategy, there is a need to assure that the realized product is likely to fulfil its purpose.

2.1.4 Alternative views of robust design methodology

Taguchi's contributions to robust design methodology can be divided into four categories—*quality philosophy*, *engineering methodology*, *experimental design* and *data analysis* (Nair *et al.* 1992). In early case studies, the experimental design aspects of Taguchi's contributions were highlighted more often than the engineering methodology aspects (Park *et al*. 2006). In other words, quantitative statistical tools were highlighted more often than the qualitative philosophies. However, this seems to have changed; several researchers have suggested that Taguchi's qualitative contributions to quality philosophy have more merit than his quantitative contributions to experimental design and data analysis (Kackar 1985, Nair *et al*. 1992, Box *et al*. 1988, Arvidsson and Gremyr 2008, Andersson 1996, Chang *et al*. 1994). Box writes that "*Professor Taguchi's quality engineering ideas are of great importance and should become part of the working knowledge of every engineer; on the other hand, many of the techniques of statistical design and analysis he employs to put these ideas into practice are often inefficient and unnecessarily complicated*" (Box, Bisgaard et al. 1988).

As a design methodology, robust design methodology can be viewed as a method for improving the design process itself. As a subset of response surface methodology, robust design methodologies are popularly used to facilitate communication between specialists on a design team (Chang and Ward 1995, Chang *et al.* 1994, Sobieszczanski-Sobieski and Haftka 1997).

2.2 GEOMETRY ASSURANCE AND LOCATING SCHEMES

In the work presented in this thesis, robust design methodology is used to address geometric variation in products. A geometrically robust design has been defined by Söderberg and Lindkvist (1999) as a design that fulfils its functional requirements and meets its constraints even when the geometry is afflicted with small manufacturing or operational variation. *Geometry assurance* is a set of activities in the concept, verification and production phase aimed at reducing the effects of geometrical variation and increase the precision of functional attributes of products (Söderberg, Lindkvist, and Carlson 2006).

Part variation stems from the manufacturing process and the wear-and-tear of manufacturing tools. This variation, together with variation in fixtures and the assembly process, lead to geometric variation of the final product. Further, the robustness of the design solution influences how variation will propagate and accumulate. Söderberg and Lindkvist state that two of the most important robustness aspects include assembly robustness and part positioning robustness (Söderberg and Lindkvist 1999). Therefore, the robustness of the design concept is an important factor to consider. The contributors to final variation are illustrated in Figure 7.

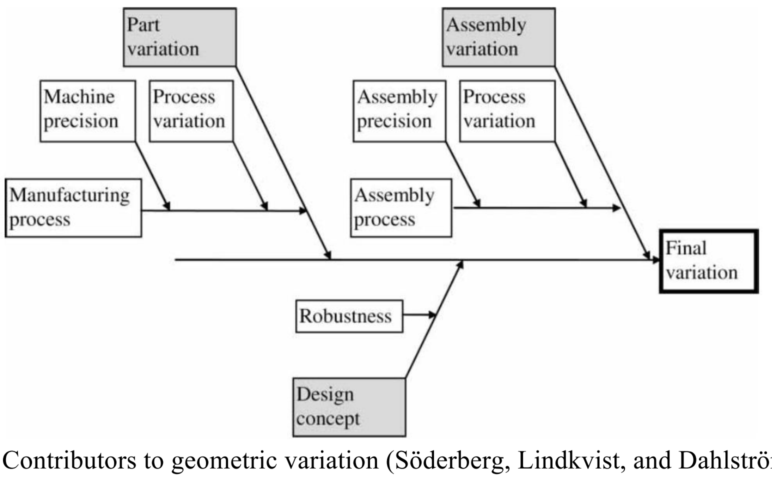

Figure 7: Contributors to geometric variation (Söderberg, Lindkvist, and Dahlström 2006).

Another important issue to consider in connection with assembly robustness is how to make the design as uncoupled as possible (Suh 2001). A coupled design leads to long tolerance chains. Hence, changes made to some part of the design may result in consequences throughout the tolerance chain. Assembly coupledness can be analysed using stability matrices, as described by Söderberg, Lindkvist, and Carlson (2006).

2.2.1 Locating schemes

A locating scheme defines how parts are related to other parts in an assembly or fixture. The purpose of a locating scheme is to lock a part or subassembly to its six degrees of freedom in space. Figure 8 shows an *orthogonal 3-2-1 locating scheme*. The *A*-points *A1*, *A2* and *A3* define the primary locating plane A and lock three degrees of freedom, *TZ*, *RX* and *RY*. The *B*-points *B1* and *B2* define the secondary locating plane *B*, perpendicular to *A*, and lock two degrees of freedom, *TX* and *RZ*. Finally, the *C*-point *C1* defines the tertiary locating plane *C*, perpendicular to *A* and *B*, and locks one degree of freedom, *TY*.

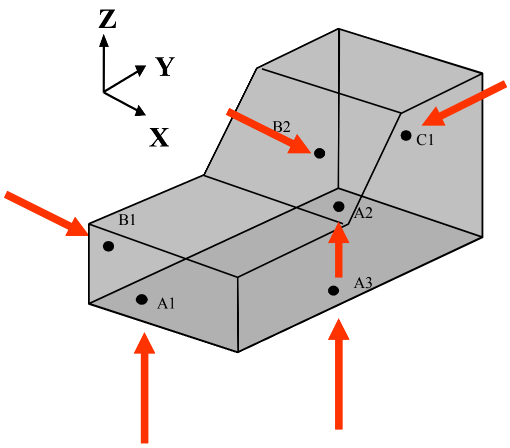

Figure 8: A 3-2-1 positioning system often used for rigid variation simulation. To the right, the *A*-points, in the center are the *B*-points and to the left the *C*-point.

Another commonly used locating scheme is the *3-point positioning system* shown in Figure 9. This system uses only three *A*-points. *A1*, *A2* and *A3* define the primary locating plane *A* and lock three degrees of freedom, *TZ*, *RX* and *RY*. However, *A1* and *A2* also define the secondary locating plane B, perpendicular to A, and lock two degrees of freedom, *TX* and *RZ*. Finally, *A1* also defines the tertiary locating plane *C*, perpendicular to *A* and *B*, and locks one degree of freedom, *TY*.

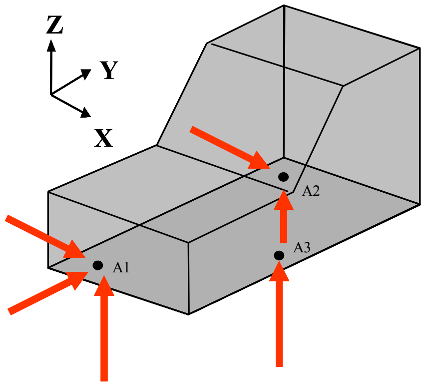

Figure 9: 3-point positioning system.

When attaching a part to an assembly, all six degrees of freedom need to be locked. The local positioning scheme of the part, or *local p-frame*, should be matched by a *target p-frame*, as shown in Figure 10.

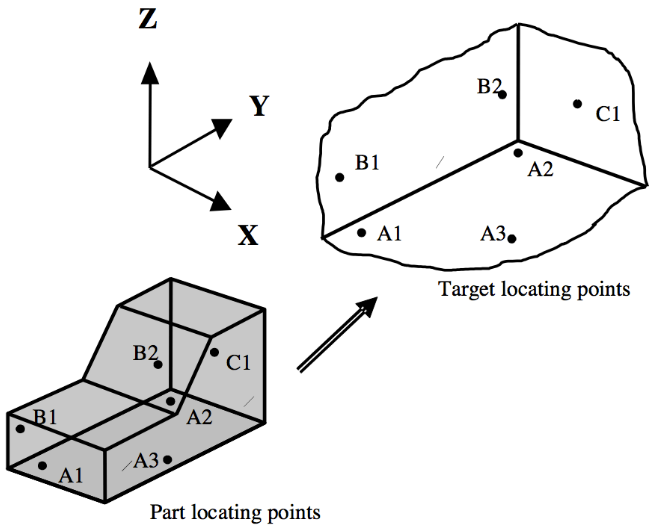

Figure 10: Locating a part to a target.

Applying variation to the locating points will then affect the positioning of the parts and, therefore, the selection of locating points should minimize the effects of variation on part position stability (Söderberg and Lindkvist 1999). Automated ways of optimizing locating schemes have been put forth (Lööf *et al.* 2009), as well as methods for the optimal allocation of tolerances on these locating points (Lööf *et al.* 2007).

2.2.2 Tolerance analysis

Tolerance analysis aims at addressing how geometric variation propagates and accumulates during assembly operation to the final product. There is an array of methods. Overviews of the research area of tolerance analysis can be found in Chase and Parkinson (1991), Hong and Chang (2002), Jami *et al.* (2008), Gao *et al.* (1998), Nigam and Turner (1995) and Lorin (2012).

Analytical methods for tolerance analysis are commonly based on Taylor expansions of the function relating input variation to output variation,

$$f(X_1, X_2, \dots, X_n) \approx f(\mu_1, \mu_2, \dots, \mu_n) + \sum_{1}^{n} \frac{\partial f(\mu_1, \mu_2, \dots, \mu_n)}{\partial x_i}(X_i - \mu_i) \qquad (2)$$

In *worst-case* tolerance analysis, the accumulated assembly tolerance T is calculated based on all input variances at their worst tolerated value t_i. This approach guarantees that manufactured products will comply with requirements but will often lead to an overly pessimistic tolerance accumulation, as the probability that all inputs will exhibit their extreme value is usually very low (Nigam and Turner 1995). A different approach is *statistical* tolerancing. Here, the tolerances are assumed to follow some stochastic distributions. In the *root-sum-square method* (RSS), the input tolerances t_i are assigned standard deviations with $\pm n\sigma_i$, for some n. Assuming small deviations from nominal values in the input tolerances, the output tolerance, T, can be approximated as (Evans 1975),

$$T = \sqrt{\sum_{1}^{n} (\frac{\partial f(\mu_1, \mu_2, \dots, \mu_n)}{\partial x_i} t_i)^2}. \quad (3)$$

If the input variation vector X_i is assumed to be normally distributed, the output variation is also normally distributed (Anderson 2003). Often, the output tolerance can be assumed to be normal under more general assumptions due to the central limit theorem. Higher order Taylor expansions can also be used (Nigam and Turner 1995, Cai *et al.* 2006).

The RSS-value can provide an overly optimistic tolerance prediction (Nigam and Turner 1995). To counter this optimism, the RSS-value is sometimes modified using a scale factor. There are also measures to account for mean value drifts and combinations of these measures. Lööf (2010) provides a compilation based on Chase and Parkinson (1991) and Wu and Tang (1998).

Deterministic methods for tolerance analyses are often computationally cheap. However, it can be difficult to derive analytical expressions and Taylor expansions. Further, the accuracy of the deterministic methods is sometimes questioned (Cai *et al.* 2006). A different approach is offered by Monte Carlo (MC) simulations, which are based on generating a large number of samples of input distributions. MC-simulations capture both linear and non-linear relationships. They may, however, require a large number of samples to draw correct inferences from these simulations. The technique can therefore be time-consuming and computationally intensive (Nigam and Turner 1995).

2.3 UNCERTAINTY QUANTIFICATION

There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know.

Donald Rumsfeld (2002)

Over the past few decades, advances in computational capabilities have cemented computer simulation of physical processes as an important tool in designing engineering systems (Oberkampf and Trucano 2002, Agarwal *et al.* 2004). In applying principles of robust design methodology and geometry assurance to processes that use these virtual tools, it becomes important to address modelling and simulation uncertainty. However, mainstream robust design methodology does not take this uncertainty into account. This is hardly surprising, since most of Taguchi's research was conducted prior to the digital revolution. As a consequence, sources of variation commonly associated with robust design methodology all relate to physical reality. Phadke (1989) classifies the following sources of uncertainty, which he calls noise factors:

1. **External**. The environmental conditions and loads to with products are exposed.
2. **Unit to unit**. The variation springing from the variation in the manufacturing process and assembly situation.
3. **Deterioration**. Functionality become increasingly divergent as products deteriorate.

These three sources all describe the inherent variation associated with the physical system or environment under consideration and are commonly referred to as *aleatory uncertainty* (Oberkampf, DeLand et al. 2002).

Uncertainty quantification is the scientific field of quantitative characterization and reduction of uncertainty in applications. As computer simulation modelling is a commonly used approach to study problems in uncertainty quantification and a framework has been developed to account for different types of uncertainty. Three different classes of uncertainty have been identified: aleatory uncertainty, *epistemic* uncertainty and *error* (Apley *et al.* 2006, Youn *et al.* 2007, Oberkampf *et al.* 2002, Agarwal *et al.* 2004):

.

1. **Aleatory uncertainty** is also known as *irreducible*, *inherent or stochastic* uncertainty or *variability*. This uncertainty is associated with the inherent variation in the physical system or environment under consideration, for example, uncertainty of incoming material, initial part geometry, tooling set-up, process set-up, and operating environment (Chen *et al.* 2004) . Aleatory uncertainty can generally be estimated by a probability or frequency distribution when sufficient information is available (Oberkampf, DeLand et al. 2002).

2. **Epistemic uncertainty** is also known as *reducible*, *subjective* or *cognitive* uncertainty. It can be defined as a potential inaccuracy associated with the deficiency in any phase or activity in the simulation process that originates in a *lack of system knowledge*, for example, uncertainty associated with the lack of knowledge in laws describing the behaviour of the system under various conditions (Chen *et al.* 2004).

3. **Error** is defined as a *recognizable* inaccuracy in any phase or activity of modelling and simulation that is *not* due to a lack of knowledge. This error can be either *acknowledged* or *unacknowledged*. An example is the uncertainty associated with the limitations of numerical methods used to construct simulation models (Chen *et al.* 2004).

There is also a distinction being made between *acknowledged* and *unacknowledged* error. Acknowledged errors are inaccuracies that are recognized by analysts, whereas unacknowledged errors are inaccuracies that are *not* recognized by analysts (Oberkampf *et al.* 2002).

Oberkampf et al. (2002) have put forth a comprehensive framework for categorizing uncertainty in activities conducted during the phases of computational modelling and engineering. Figure 11 visualizes the framework. The simulation process can be divided into six phases, each of which introduces its own set of uncertainty. The following sections outline these phases and are an adaptation of the detailed description found in Oberkampf et al. (2002).

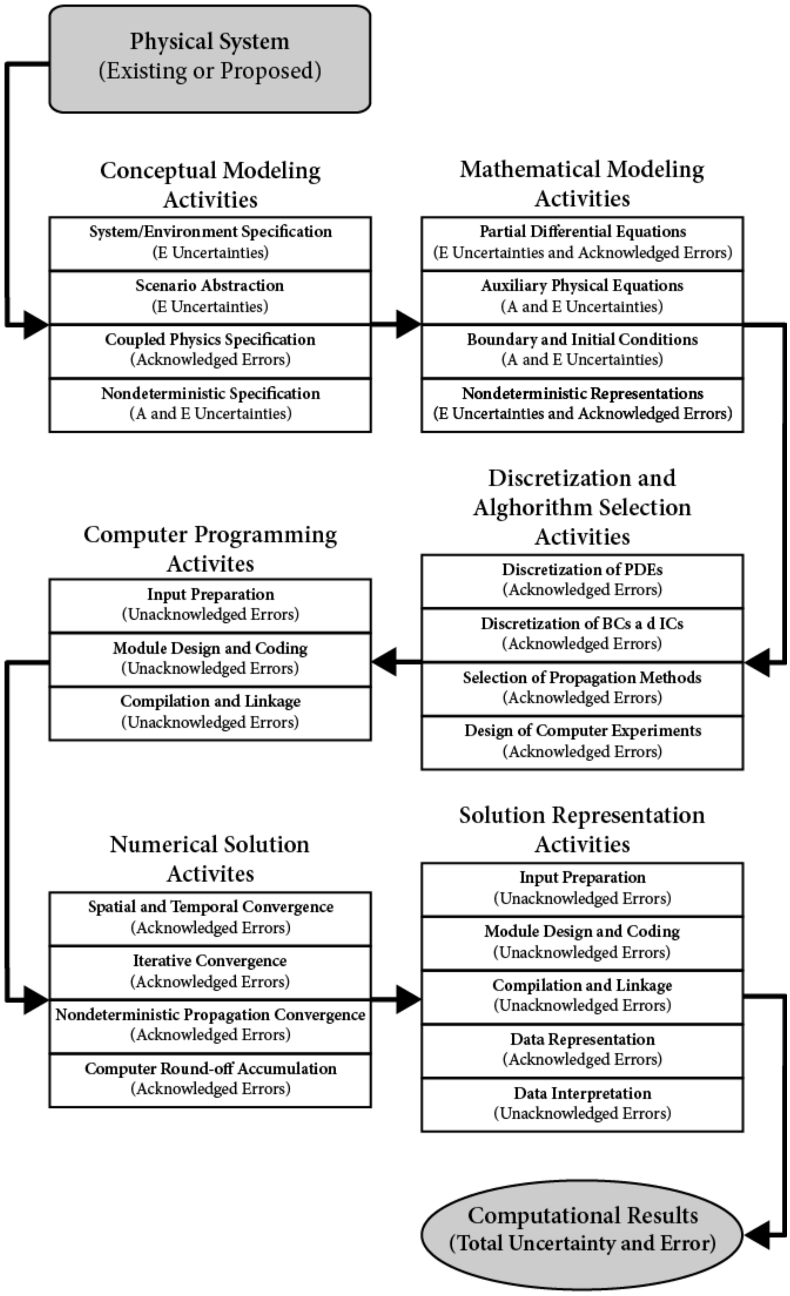

Figure 11: Uncertainty in modelling and simulation (Oberkampf *et al.* 2002).

2.3.1 Conceptual modelling of the physical system

This phase relates to the conceptual modelling of the system, before any mathematical or simulation models have been initiated. The initial step is *system/environment specification*—the process of determining which physical events should be considered and where to define the boundaries between system and environment. This phase introduces epistemic uncertainty. When modelling physical events with mathematical or simulation models, *scenario abstraction* is a prerequisite. For instance, dynamic phenomena will often be simplified into quasi-static models. After systems, environments and scenarios have been specified, options for possible *physics couplings* should be identified. Another activity conducted during this phase is to specify what system and material characteristics need to be treated non-deterministically.

2.3.2 *Mathematical modelling of the conceptual model*

This phase is concerned with translating the conceptual model into detailed and precise mathematical problems, i.e. analytical statements of the problem. Even the most complex computer simulation is composed of many mathematical sub-models. The mathematical modelling includes the complete specification of all *partial differential equations* (PDEs), *auxiliary physical conditions*, *boundary conditions* (BCs) and *initial conditions* (ICs). Uncertainty in the PDEs can for instance be found in the conservation equations for mass, momentum and energy, which form the basis of the CFD and FEA simulations. This uncertainty can be either epistemic or acknowledged errors. Examples of uncertainty in the auxiliary physical conditions may be limitations in turbulence models of CFD simulations or in material-constitutive equations in FEA. Uncertainty in BCs and ICs include uncertainty in loads and geometries. By this definition, geometry assurance is an example of an activity where this uncertainty is addressed. This uncertainty can be both aleatory and epistemic. *Nondeterministic representation* activities are associated with assigning PDFs to uncertainty parameters.

2.3.3 *Discretisation and algorithm selection*

A conversion from continuous to discrete mathematics is usually needed to calculate a numerical solution. In this phase, all of the spatial and temporal differencing methods, discretized BCs, discretized geometric boundaries and grid generation methods are specified in analytical form. Algorithms are prescribed, but the spatial and temporal step sizes are not specified. Another activity is specifying the methodology that will be used to accommodate the nondeterministic aspect of the problem, such as Monte Carlo or response surface methods.

2.3.4 *Computer programming of the discrete model*

Software errors are often an unacknowledged source of simulation error. *Input preparation* refers to how the mathematical model is converted into data elements usable by the software. Module design, coding, compilation and linkage refer to the construction of the software itself. Oberkampf suggests that this is the phase with the highest level of maturity because of decades of programming development and software quality assurance efforts.

2.3.5 *Numerical solution of the computer program model*

In this phase, numerical solutions are computed. This phase includes uncertainty associated with *spatial, temporal* and *iterative convergence*. An example of spatial convergence is mesh density errors, whereas temporal convergence concerns time steps of dynamic simulations. Iterative convergence is usually an issue when working with CFD simulations.

2.3.6 *Representation of the numerical solution*

The final phase deals with the representation and interpretation of simulation results. Computer simulations generally have millions of data points and in order to represent these points, post-processing is needed. A common tool is color-coded, three-dimensional graphical visualization. Another method to draw conclusions would be to extract mean, minimum and maximum values of a simulation result. These activities are dependent on interpretation and as such, may introduce unique types of error.

2.4 GENETIC ALGORITHMS

"One general law, leading to the advancement of all organic beings, namely, multiply, vary, let the strongest live and the weakest die."
Charles Darwin (1859)

Genetic algorithms (GA) are search procedures that mimic the mechanics of natural selection and genetics (Goldberg 2013). For optimization problems with large numbers of variables, traditional optimization schemes tend to be overly time-consuming. For such problems, genetic algorithms are a powerful tool. For a given engineering system, the algorithm starts by generating a number of system states using random input vectors. These vectors constitute the first generation. The systems that perform well form the basis of the subsequent generation by combining their input vectors using *crossover* and *mutation* algorithms. As this processes are repeated throughout a number of generations, well-performing input vectors can be identified. With some modifications, genetic algorithms can be readily applied to permutation optimization problems.

2.4.1 Crossover algorithms

Crossover algorithms combine two successful input vectors from a previous generation, called the *parent vectors*, into two *child vectors*.

There is an array of crossover algorithms specifically for combinatorial problems. A common version *is partially-mapped* crossover, introduced by Goldberg and Lingle (1985).

Consider two parent vectors:

$$\begin{aligned} P_1 &= [2\ 3\ 4\ 5\ 6\ 1] \\ P_2 &= [3\ 2\ 6\ 1\ 4\ 5] \end{aligned} \tag{4}$$

In a single-point crossover at random, two children are obtained

$$\begin{aligned} C_1 &= [2\ 3\ 4\ 1\ 4\ 5] \\ C_2 &= [3\ 2\ 6\ 5\ 6\ 1] \end{aligned} \tag{5}$$

Both of these children vectors are invalid; C_1 has two occurrences of the number 4 and is missing the number 6, whereas C_2 has two occurrences of the number 6 and is missing the number 4. This inconsistency is easily remedied simply by randomly replacing one of the 4-valued elements in C_1 with a 6, and replacing one of the 6-valued elements in C_2 with a 4. This would lead to the C_1 and C_2 being modified into:

$$\begin{aligned} C_1 &= [2\ 3\ \mathbf{6}\ 1\ 4\ 5] \\ C_2 &= [3\ 2\ 6\ 5\ \mathbf{4}\ 1] \end{aligned} \tag{6}$$

where entries in boldface were randomly changed to give a valid permutation.

Partially-mapped crossover is a common and generally well-performing crossover algorithm. Another noteworthy algorithm is the *cycle-crossover* algorithm (Oliver *et al.* 1987, Michalewicz 2013), which has the potential benefit of retaining the relative order of entries from parents to children. Other notable crossover methods are *order* crossover (Davis 1985), *inver-over* crossover (Tao and Michalewicz 1998) *order-based crossover* (Syswerda 1991), as well as *adjacency-based* and *ordinal-based* crossovers (Grefenstette *et al.* 1985). Each of these algorithms have their own weaknesses and benefits. Simon (2013) covers the benefits and weaknesses of each of these methods in further detail.

2.4.2 Mutation algorithms

Mutation is the process with which a single vector randomly changes some elements. Like crossovers, mutations be performed using many different algorithms. *Inversion* reverses the order of the vector elements between two randomly selected indices (Beyer and Schwefel 2002).

$$\begin{aligned} V &= [2\ 3\ \mathbf{4\ 5\ 6\ 1}\ 8\ 7] \\ V_m &= [2\ 3\ \mathbf{1\ 6\ 5\ 4}\ 8\ 7] \end{aligned} \tag{7}$$

Another algorithm is insertion (Fogel 1988), which moves one element from position *i* to position *k*, where *i* and *k* are randomly generated. For instance, if *i* is equal to 4 and *k* is equal to 7, the mutation becomes the following:

$$\begin{aligned} V &= [2\ 3\ 4\ \mathbf{5}\ 6\ 1\ 8\ 7] \\ V_m &= [2\ 3\ 4\ 6\ 1\ 8\ \mathbf{5}\ 7] \end{aligned} \tag{8}$$

Another method is *displacement* or *shifting,* which is a generalization of insertion (Beyer and Schwefel 2002). Here, instead of choosing only one element to move, a sequence of elements, in which the length is determined by the random variable *q,* is moved from position *i* to position *k*. A third method is *reciprocal exchange* (Banzhaf 1990), also known as *2-exchange mutation* (Beyer and Schwefel 2002). This algorithm randomly generates two indices *i* and *k*, and switches the values of the corresponding elements.

$$\begin{aligned} V &= [2\ 3\ 4\ \mathbf{5}\ 6\ 1\ \mathbf{8}\ 7] \\ V_m &= [2\ 3\ 4\ \mathbf{8}\ 6\ 1\ \mathbf{5}\ 7] \end{aligned} \tag{9}$$

Mutations are generally not performed on every new child. Instead, a probability p_m determines the mutation rate of the children. Further, different mutation algorithms can be combined or used in parallel with varying mutation rates.

2.4.3 Selection and termination criteria

In order to breed the children, a selection mechanism for selecting the parents is needed. Selection criteria can be based on either fitness value, or relative ranking of, their performance (Whitley 1989). An example of the former *is roulette-wheel selection*, also known as *fitness-proportional selection*, where the chance of being selected is proportional to their fitness, or their relative rank.

Termination criteria state the conditions under which the genetic algorithm loop should be terminated. Ideally, termination should occur when results converge and a globally optimal candidate has been found. Convergence is, however, not easy to confirm. Even when the algorithm has apparently converged, a statistically improbable mutation or recombination event might yield a significant improvement in the solution (Simon 2013). For permutation problems, convergence is even more difficult to achieve without generating duplicate solutions.

An alternative termination criterion is simply to stop the loop after a given number of generations. Although this approach does not guarantee an optimal candidate yield, it benefits from an ease of implementability and simulation time estimation.

2.5 THE AEROSPACE INDUSTRY

Aircraft engine manufacturing is dominated by three large companies: General Electric Aircraft Engines (GE), Pratt & Whitney (P&W) and Rolls-Royce (RR). However, due to the high development costs of new engines, these companies prefer to organize product development through international partnerships. Typically, a network of Risk-and-revenue Sharing Partners (RSPs) share development risks and cost, as well as subsequent profits (Högman 2011). The RSPs are generally first-tier suppliers of engine components. In a typical new engine project, the main engine manufacture holds 50-70% of the stakes, and the rest is divided among the top-tier suppliers (Prencipe 1998).

In the aerospace industry, a move towards probabilistic design practices has been recognized as a potential game-changer. In a report commissioned by NASA and compiled by Zang *et al.* (2002), the principal benefits of uncertainty-based design in the aerospace industry include the following:

1. Confidence in analysis tools will increase.
2. Design cycle time, cost, and risk will be reduced.
3. System performance will increase while ensuring that reliability requirements are met.
4. Designs will be more robust.
5. The methodology can assess systems at off-nominal conditions.
6. Use of composite structures will increase.

Because of these benefits, engine manufacturers have taken significant steps towards probabilistic design methods. GE adapted Design for Six Sigma (DfSS) in 1995, a methodology where probabilistic methods were championed over deterministic approaches (Henderson and Evans 2000, Eckes 2002). Meanwhile, Pratt & Whitney has launched their own Design for Variation (DFV) initiative, described in detail by Reinman *et al.* (2012). However, as today's engine projects are collaborative projects with high involvement by the RSPs, there is a need to standardize and integrate these processes. This need has been recognized by the European Union, who funded the *Collaborative & Robust Engineering using Simulation Capability Enabling Next Design Optimization* (CRESCENDO) project. This €55M research endeavour ran between 2009 and 2014, involved 14 European aeronautics companies, including Rolls-Royce and GKN, as well a number of academic institutions, research centres and software companies (Coleman 2011). One of the key aims of this project was to develop collaborative probabilistic methods for the aerospace industry. Since its end in 2013, it was followed by the *Thermal Overall Integrated Conception of Aircraft* (TOICA) project, a 3-year European €26.5M project that focused on thermal aspects of the same problems with mainly the same participants.

Although these endeavours attest to the determination of the aerospace industry to adopt probabilistic methods, there are many barriers to overcome. In their report, Zang *et al.* (2002) also list barriers to implementation:

1. Industry feels comfortable with traditional design methods.
2. Few demonstrations of the benefits of uncertainty-based design methods are available.
3. Current uncertainty-based design methods are more complex and much more computationally expensive than deterministic methods.
4. Characterization of structural imperfections and uncertainties necessary to facilitate accurate analysis and design of the structure is time-consuming and is highly dependent on structural configuration, material system, and manufacturing processes.
5. There is a dearth of statistical process control activity in aerodynamics.
6. Effective approaches for characterizing model form error are lacking.
7. There are no dependable approaches to uncertainty quantification for nonlinear problems.
8. Characterization of uncertainties for use in control is inadequate.
9. Methods for mapping probabilistic parameter uncertainties into norm-bounded uncertainties do not exist.
10. Existing probabilistic analysis tools are not well suited to handle the time and frequency domain response quantities that are typically used in the analysis of closed-loop dynamical systems.
11. No methods are available for optimization under non-probabilistic uncertainties.
12. Current methods for optimization under uncertainty are too expensive for use with high-fidelity analysis tools in many disciplines.
13. Extending uncertainty analysis and optimization to applications involving multiple disciplines compound the complexity and cost.
14. Researchers and analysts lack training in statistical methods and probabilistic assessment.

Some of these barriers are purely technical, as uncertainty-based methods are generally more complex and computationally expensive than their deterministic counterparts. However, some barriers are more related to methodology; an example is the lack of approaches for assessing model form error. Overcoming these barriers has organizational implications, as a switch to uncertainty-based methodologies at an engine manufacturer will propagate to its RSPs and suppliers.

Unfortunately, the existence of these barriers cement deterministic simulation practices as the norm in the aerospace industry (Sudret and Der Kiureghian 2000, Ullman 2001, Agarwal *et al.* 2004, Zang *et al.* 2002, Oberkampf and Roy 2010). Deterministic simulations are limited by their inherent lack of quantified knowledge of variation and uncertainty. To remedy this limitation, a *factor of safety* is a common engineering approach for mitigating risks within deterministic practices. Factors of safety are used to account for both physical uncertainty, such as manufacturing tolerances and operating conditions, as well as model uncertainty and error in simulation. In aerospace contexts, factors of safety are set from 1.2 to 3 (Keane and Nair 2005, Zang *et al.* 2002).

However, a factor of safety approach is problematic in two ways. Firstly, factors of safety are not straightforward to assign, especially when working with new materials and design concepts, and when there are limited experimental data (Keane and Nair 2005, Zang *et al.* 2002). Secondly, factors of safety lead to increased costs (Choi *et al.* 2006, Ebro and Howard 2016) and conservative designs that are excessively heavy. The weight penalties are amplified in a vicious circle; as heavier structures demand larger engines and additional fuel, they in turn need more structural support, which require increasingly more power, and so on (Shlapak 2002).

2.6 JET ENGINE TECHNOLOGY

In this section, a brief introduction is provided to jet engine technology in general. Hünecke (1997) provides a more detailed look at jet engine design.

A gas turbine engine uses the thermodynamic cycle known as the Bryton cycle. Air is sucked through the inlet and compressed. In the combustor chamber, fuel is injected and mixed with compressed air. As the mixture is ignited, the resulting volume expansion pushes the mixture through the turbine. In the turbine, a part of the energy content is used for powering the fan and compressor stages. The remainder is used for jet propulsion.

For pure jet propulsion, all the thrust comes from the core flow passing through the combustor. In the commercial aircraft engines of today, only a small portion of the air sucked through the fan enters the core. Instead, the fan acts like a propeller, where as much as 90% of the air is bypassed from the core.

The compressor is directly connected to the turbine through a shaft, which means that they are spinning at the same rate. However, most engines have two, or more, stages. In a two-stage turbofan, the low-pressure stage (marked in green on Figure 12) consists of the fan, the low-pressure turbine and low-pressure compressor, all mounted on the same shaft. The high-pressure stage (marked in purple) consists of a high-pressure compressor and high-pressure turbine, mounted on a hollow shaft co-axial to the other shaft. The shafts are spinning at different rates for optimal engine operation. As the spinning rate is a trade-off between the optimal compressor and turbine performance, a two- or three-stage engine increases engine efficiency.

The commercial turbofan engines of today are designed to be fuel-efficient. This fuel-efficiency is accomplished by increasing the bypass ratio, which in turn implies large fan diameters. Modern engines are significantly larger than engines designed 30 years ago. The components inside the engine have also increased in size.

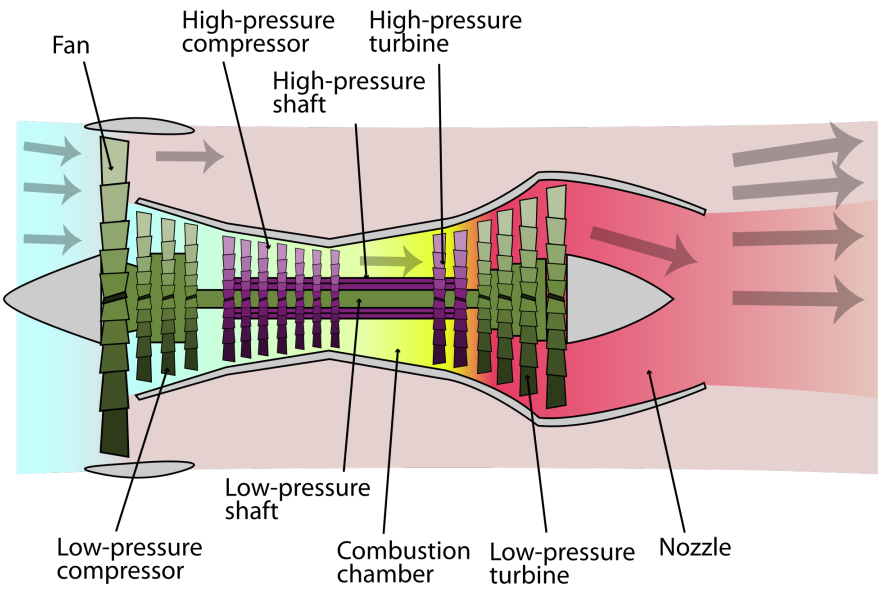

Figure 12: Diagram of a high-bypass jet engine. Image credit: Wikipedia.

2.6.1 *Turbine rear structures*

The publications included in this thesis all focus on the same application—the design of the turbine rear structure (TRS) of a commercial turbofan engine, shown in Figure 13.

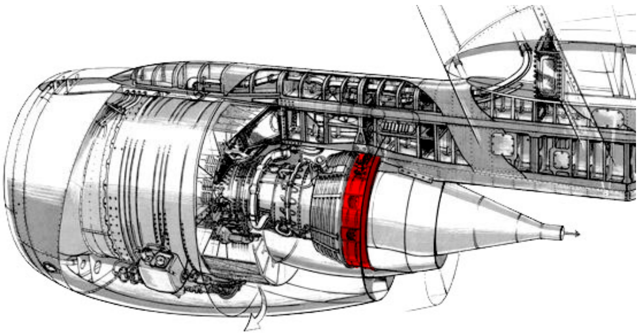

Figure 13: Turbine rear structure (highlighted in red).

TRSs are found in all sizes of turbofan engines and thus come in all shapes and sizes. Figure 14 shows the TRSs of differently sized engines. Geometry definitions are unique for each TRS and parts are rarely reused but the general design elements remain the same. This similarity between parts benefits a platform-based design approach.

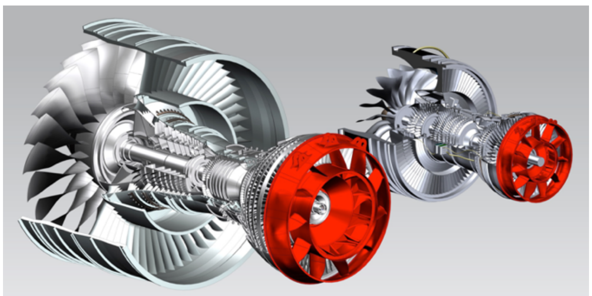

Figure 14: Turbine rear structures on different size engines (highlighted in red).

The TRS is located at the rear part of an engine, where it attaches the engine to the aircraft pylon, while holding the low-pressure turbine bearing in place. It also redirects the hot exhaust flow from the combustion chamber (Forslund 2012). Modern TRSs are made up of nickel-based super-alloys that perform well at high temperatures. They are fabricated assemblies, containing cast, forged and sheet metal parts. The TRS is defined by three different sections: the hub, which is the inner section connected to the bearing, the shroud, which is the outer ring connected to the low-pressure-turbine frame, and the vanes, which are the aerodynamic spokes connecting the hub to the shroud.

Different design solutions exist for splitting hub, vane, and shroud sections into parts. The assembly consists of locking these parts into fixtures and welding them together. Ingoing parts have some degree of geometric variation. This part variation propagates through the fixturing and welding process into the final assembly and ultimately affects the performance of the engine. The assembly variation is dependent on part design, placement of fixture reference points and welding sequence.

Producibility is a constraint for the design process as designs optimised from a functionality perspective can be expensive or unfeasible to realise in practice (Runnemalm *et al.* 2009, Madrid *et al.* 2016). One of the key limitations of producibility is geometrical variation, i.e. the dimensions of a manufactured product deviate from the nominal geometry. TRSs are usually welded assemblies consisting of cast, wrought and sheet metal parts. The ingoing parts all have some degree of geometrical variation. This part variation propagates through the fixturing and welding process into the final assembly and ultimately affects the performance of the engine.

There are hundreds of design requirements for TRSs, ranging from aerodynamic, structural and thermal performance to producibility. These design requirements are highly linked. For instance, the aerodynamic flow of hot exhaust gas heats the structure to temperatures around 600°C. The resulting thermal expansion of the material puts significant stress on the structure (Isaksson 1998). The constant heating and cooling of the structure in-between flights creates low-cycle fatigue. This material fatigue is a limiting factor for the number of flights that a single component can safely withstand (Lodeby *et al.* 1999).

3 RESEARCH APPROACH

This chapter briefly outlines different approaches for scientific study. Further, it discusses the research approach and methods applied in this research project.

3.1 BACKGROUND

Different disciplines have varying traditions for how to conduct credible research. A clear distinction is made between *qualitative* and *quantitative* research. Quantitative research refers to the systematic empirical investigation by means of statistical, mathematical or computational techniques (Given 2011). Qualitative research, on the other hand, is the process of trying to get a better understanding of the complexities of human experience and take action based on that understanding (Marshall and Rossman 2006). In other words, quantitative research provides the answers to *what*, *where*, and *when*, whereas qualitative research provides answers to questions beginning with *why* and *how*.

Research that includes both quantitative and qualitative approaches is called *mixed-methods research*. Mixed methods research can be defined as research in which the investigator collects and analyses data, integrates the findings, and draws inferences using both qualitative and quantitative approaches or methods in a single study or program of inquiry (Tashakkori and Creswell 2007).

On a more fundamental level, Crotty (1998) introduced a framework consisting of four levels that constitutes the basic elements of any research process. These levels include:

- *Methods*: the techniques and procedures used to gather and analyse data related to some research hypothesis.

- *Methodology*: strategy, plan of action, process or design behind the choice and use of particular methods and linking the choice and use of methods to the desired outcomes.

- *Theoretical perspective*: the philosophical stance informing the methodology, thus providing a context for the process while grounding the logic and criteria inherent in the research context.

- *Epistemology*: the theory of knowledge embedded in the theoretical perspective and, thereby, methodology.

Figure 15 shows the above-mentioned elements sorted in ascending order.

Paradigm worldview
(beliefs, e.g., epistemology, ontology)

↓

Theoretical lens
(e.g., feminist, racial, social science theories)

↓

Methodological Approach
(e.g., ethnography, experiments, mixed methods)

↓

Methods of Data Collection
(e.g., interviews, checklists, instruments)

Figure 15: Four Levels for Developing a Research Study (Creswell 2009)

3.1.1 Design research methodology

The research presented in this thesis relates to product design. *Design Research Methodology* (DRM) is a framework proposed by Blessing (2002), which was put forth in order to guarantee quality in design research. Blessing suggests dividing design research into four phases:

1. *Research Clarification*: The main goal of this phase is to find a *success criterion* by which to evaluate the outcome of the research. To find the right criterion, a researcher needs to understand the situation at hand. Traditionally, a preliminary literature review is performed in order to clarify research goals.

2. *Descriptive Study I:* In this phase, the current situation is studied. The objective is to understand and clarify the situation and identify which factors might be addressed to improve the situation. In this phase, a detailed literature review is made and if a knowledge gap should arise, empirical studies may be conducted.

3. *Prescriptive Study*: This phase aims at improving the current situation. Methods and tools are developed in order to reach the desired state.

4. *Descriptive Study II:* In this phase, the methods and tools proposed in the prescriptive study are evaluated to verify that they achieve the intended effects.

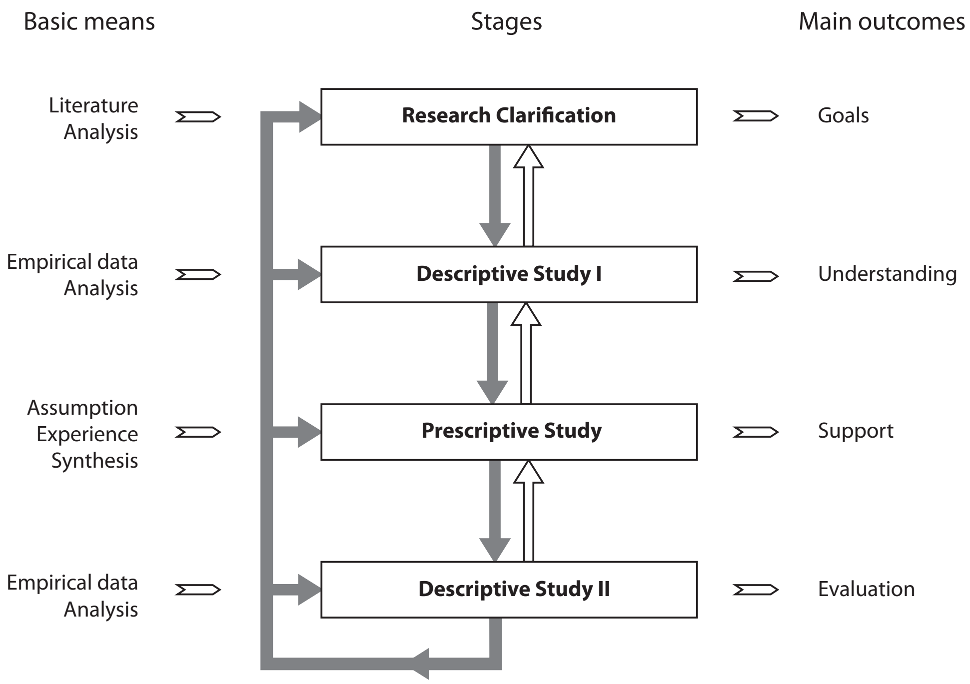

Figure 16: The DRM framework, redrawn from Blessing and Chakrabarti (2009).

These four phases do not necessarily need to be performed in sequential order but are rather designed to encourage iterations.

3.1.1 Case study research

Case studies are a common strategy for conducting qualitative research within the design area. According to Yin (2009), a case study investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident.

Numerous methods for collecting data within the setting of a case study are available. A common method within a case study is performing interviews. Blessing and Chakrabarti (2009) differentiate between three classes of interviews:

1. *Fully structured interviews* are characterized by exactly phrased questions that are asked in a predefined order.

2. *Semi-structured interviews* ask predefined questions, but the phrasing and order of the questions can vary to get a better interview flow. Questions can also be given an explanation or be excluded if found irrelevant for a particular respondent.

3. *Unstructured interviews* are similar to a general conversation, during which the interviewer discusses a general area of interest with the respondent.

A common misconception about case-study research is that a single case study cannot contribute to scientific development on the theory that it is hard to generalize findings from a single case. This notion has been eloquently rebutted by Flyvbjerg (2006), who argued that the closeness of the case study to real-life situations in all their complexity is important in two respects:

1. Case studies are important for the development of a nuanced view of reality, including the view that human behaviour cannot be meaningfully understood as simply the rule-governed acts found at the lowest levels of learning processes and in a great deal of theory.

2. Cases are important for the learning process of researchers in developing the skills needed to conduct good research. If researchers should wish to develop their own skills to a higher level, concrete and context dependent experience is just as central to them as to professionals learning any other specific skill.

In conclusion, Flyvbjerg writes that "great distance to the object of study and lack of feedback easily lead to a stultified learning process, which in research can lead to ritual academic blind alleys, where the effect and usefulness of research becomes unclear and untested".

It can also be argued that the case study is ideal for using the type of test that Karl Popper (1959) called "falsification"—if one observation alone would not fit a proposition, the proposition would be considered invalid and must therefore either be revised or rejected.

3.1.2 Verification and validation of the results

There is a wide consensus that verification and validation are important activities in order to ensure quality, both in scientific research as well as in engineering applications (Maropoulos and Ceglarek 2010, Chen *et al.* 2004, Buur 1990, Pedersen *et al.* 2000). However, the exact meaning of these two terms seem to be disputed; "validation" and "verification" have been defined in a variety of ways in different contexts, not necessarily in compliance with standard definitions. Journal articles and textbooks sometimes use "verification" and "validation" interchangeably or in some cases refer to "verification, validation and testing" as if they were a single concept (Maropoulos and Ceglarek 2010). Barlas and Carpenter (1990) note that the meaning of "verification" and "validation" are swapped in modelling literature and engineering research. In modelling research, *verification* refers to internal consistency, whereas *validation* refers to the justification of knowledge claims. In engineering research, *validation* refers to internal consistency, whereas *verification* deals with the justification of knowledge claims.

In this thesis, we define verification and validation in such a way that verification asks the question "*Did we do it in the right way?*", whereas validation focuses on "*Did we do the right thing?"*.

Consistent with this definition, Chen *et al.* (2004) subscribe to the modelling research classification in their definitions of verification and validation of simulations. They define *model verification* as the assessment of the accuracy of the solution of a mathematical model. *Model validation*, on the other hand, is defined as the assessment of how accurately the mathematical model represents the real world application. Chen et al. also note the limitation in that model validation approaches are restricted to validation at a particular design setting. There is no guarantee that the conclusion can be extended to the entire design space. They further suggest that there are two traditional validation approaches: 1) subjective and 2) quantitative comparisons of model predictions and reality. Subjective validation is usually performed by visual inspection of the model and results, and is therefore often dependent on graphical interfaces. Quantitative comparisons look at measures of the difference between model and real world but are also subjective when defining acceptable magnitudes of the measures.

For the verification of qualitative research, different methods are applied. Buur (1990) presents two verification approaches within engineering design. One approach is *verification by acceptance*. This approach suggests that scientific contributions are verified when after undergoing peer review, they are accepted for publication. Another approach is *logical verification*. Buur includes four levels in this step:

1. *Consistency*. There should be no internal conflict between the various elements of the research.

2. *Coherence*. The research results should agree with well-established and successful methods.

3. *Completeness*. All observed phenomena should be explained or rejected by the findings.

4. *Ability to explain phenomena*. Case studies and design problems can be explained by the results.

3.1.3 Technology readiness levels

In the existing taxonomy of research methods (Williamson 2002), a distinction is made between *basic research* and *applied research*; basic research is directed towards *theory building* and contributes to the advancement of the general knowledge in society, whereas applied research targets a specific problem. This distinction links applied research more closely to engineering development.

The scientific research presented in this thesis is connected to the development of engineering technology and methodology. Being applied research, it aims to be conducted in such a way that its findings are transferrable to industrial settings. At the company with which this research was conducted, the established framework of *technology readiness levels* (TRLs) is used to manage the maturity development of technology. Table 1 lists the nine technology levels, as defined by the U.S. Department of Defense (DoD 2011). These levels are as applicable to simulation tools and engineering methodology as to other technical solutions.

Table 1: Technology Readiness Levels. Adapted from US Dept. of Defense Guidance (DoD 2011).

RL	Definition	Description	Supporting Information
1	*Basic principles observed and reported.*	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.
2	*Technology concept and/or application formulated.*	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
3	*Analytical and experimental critical function and/or characteristic proof of concept.*	Active R&D is initiated. This includes analytical and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
4	*Component and/or breadboard validation in a laboratory environment.*	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in a laboratory setting.	System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
5	*Component and/or breadboard validation in a relevant environment.*	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	Results of testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare against expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?
6	*System/subsystem model or prototype demonstration in a relevant environment.*	Representative model or prototype system, well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in the demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results of laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What were the plans, options, or actions to resolve problems before moving to the next level?
7	*System prototype demonstration in an operational environment.*	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an air-craft, vehicle or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What /were the plans, options, or actions to resolve problems before moving to the next level?
8	*Actual system completed and qualified through test and demonstration.*	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What were the plans, options, or actions to resolve problems before finalizing the design?
9	*Actual system proven through successful mission operations.*	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.	OT&E reports.

3.2 ELEMENTS USED IN THIS RESEARCH

The research presented includes both quantitative and qualitative elements and is therefore addressed using a mixed methods approach. The aim is to investigate the merit of methods of geometry assurance and robust design based on the qualitative assessment of industrial need with the support of quantitative evidence.

The relationship between the DRM phases and the research questions are outlined in Table 2.

Table 2: The relationship between the DRM phases and the research questions

	RQI	**RQII**	**RQIII**
Research Clarification	x	x	x
Descriptive Study I	x		
Prescriptive Study		x	
Descriptive Study II			x

The Research Clarification phase includes defining appropriate research questions, whereby the success criterion may be defined as the extent to which these questions are answered in the subsequent research. The Descriptive Study I phase involves understanding the current situation, and in particular, identifying the barriers inquired in Research Question I.

To accommodate these two phases, a literature review was conducted. The results of the literature review are accounted for in Chapter 2, as well as, to a varying extent, in the frame-of-reference sections of the publications. However, as the research was performed in an industrial setting, the review of academic literature needed to be complemented with knowledge gathering from within the company. This was accomplished by reviewing in-house documentation, including current design practices, as well as conducting a series of semi-structured interviews with company employees. These interview studies are subject to certain restrictions due to the proprietary nature of industrial information. Nevertheless, they are presented to a varying extent throughout the publications. Paper F provides the most thorough account of these interview studies.

The Prescriptive Study phase involves developing methods and tools for implementing geometry assurance in multidisciplinary simulations in industrial settings, as defined by Research Question II. These tools are described in the case studies that are conducted in the publications.

The Descriptive Study II phase is the evaluative phase, where the results from the case studies are discussed, and conclusions are drawn. These relate to Research Question III, which assesses the role of geometry assurance in aerospace structure design.

As mentioned in the introduction, this research is motivated by a *research challenge* and an *industrial opportunity*. To maximize the effect of this research, while avoiding the pitfalls of "ritual academic blind alleys" described by Flyvbjerg (2006), case studies was the selected method for conducting this research.

Table 3 sorts the elements used in this research according to the framework put forth by Crotty (1998).

Table 3: Elements used in this research in the Crotty framework (1998)

Epistemology	**Theoretical Perspective**	**Methodology**	**Methods**
Objectivism Constructivism Subjectivism	Robust Design Philosophy Virtual Product Development	Design Research Methodology Experimental Research Design of Experiments Survey Research	*Qualitative:* Case Studies Interviews Literature review *Quantitative:* Geometry Assurance Statistical Analysis Monte Carlo Methods Regression Analysis Genetic Algorithms

For the verification and validation of the quantitative parts of the thesis—simulation methods and results–working closely with industry has been advantageous as its simulation methods have been put through extensive verification and validation, in accordance with TRL standards, to comply with government regulations. Verification was handled through internal review and adherence to standards and design practices, and validation was performed through comparisons with physical testing. In order to benefit from this extensive work, a concerted effort to conform to these standards was made. The software used, as well as the methods employed, has to the largest extent possible been the same as those used at the company.

Nevertheless, the work presented in this thesis is original research, which has the inherent implication that unvalidated and unverified elements might be part of the process. For the verification of qualitative parts, the framework put forth by Buur (1990) was used.

As for technology readiness levels, the research proposal defines the work presented in this thesis to lie between TRL 3 and TRL 6, which suggests proceeding from proof of concept to testing in a relevant environment. For engineering methodology and simulation tools, testing in a relevant environment implies using representative and realistic models, analyses and environments.

4 RESULTS

This chapter will provide a short summary of the results gained from the work that formed the basis of the appended papers in this thesis.

4.1 SUMMARY OF APPENDED PAPERS

4.1.1 Paper A—Multidisciplinary Robustness of Aero Engine Structures

In this paper, a method for performing multidisciplinary studies to quantify geometric uncertainty was introduced. The tool presented—a multidisciplinary simulation environment where parameterized CAD models can be analysed in batch—was reused in all other papers. The objective of this initial study was to demonstrate the capability of the multidisciplinary simulation environment in dealing with geometric robustness.

In a demonstrative case study, the platform was used to analyse a turbine rear structure with specific attention being paid to the assembly of the mount lug T-sectors. To simulate non-nominal assembly, geometric variation was introduced onto CAD geometries, accomplished by applying random Gaussian variation with a standard deviation of ±1 mm to the 3-point locating scheme attaching the T-sector to the fixture. The magnitude of this variation was exaggeratedly conservative and not based on any experimental data. Figure 17 visualizes this variation.

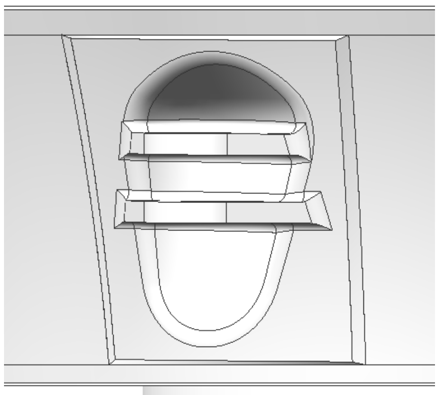

Figure 17: Assembly variation can be seen in connecting edges.

A Monte Carlo analysis with a total of 50 randomized simulations was then executed in the multidisciplinary simulation environment, evaluating 13 different thermal and structural outputs, as well as mass. Some of the interesting results were two- and three-fold increases in thermal stress for some deviated geometries. However, the CAD model did not create a realistic smooth weld in the interface between parts, something that created sharp discontinuous points where stresses were concentrated. Figure 18 shows these effects.

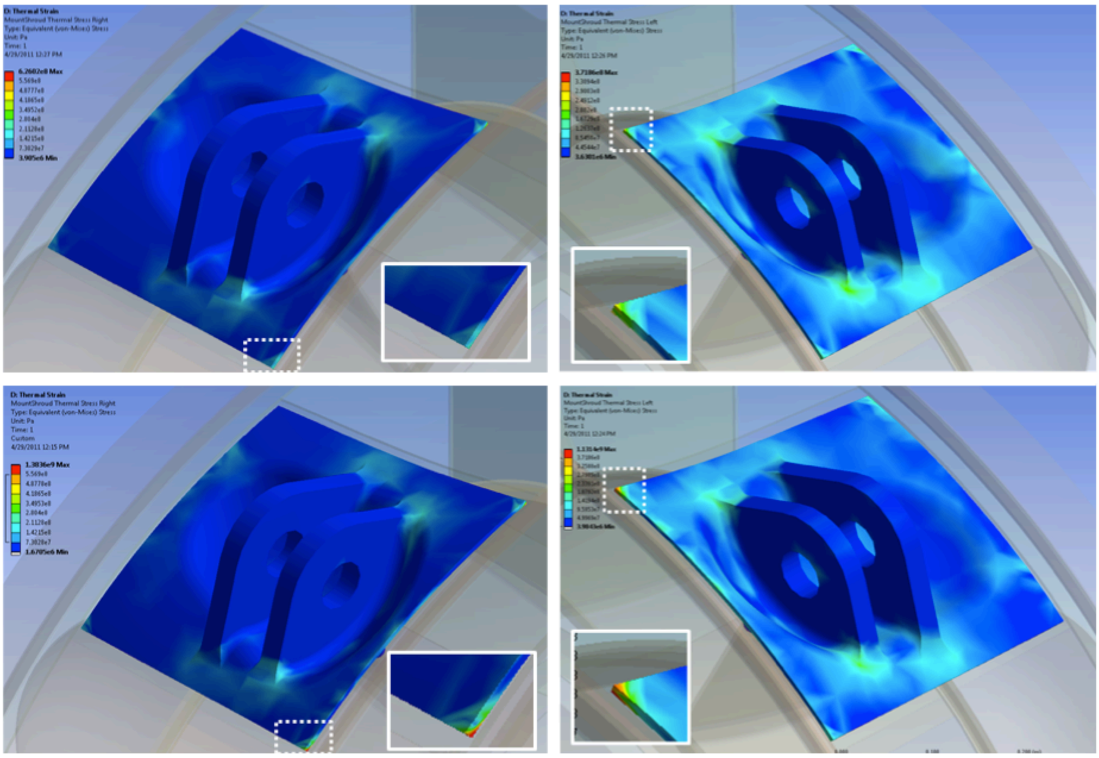

Figure 18: Thermal stress, nominal and maximum, left mount shroud (left) and right mount shroud (right).

Paper A concluded that the multidisciplinary simulation environment represented the path forward for evaluating functional robustness; as a consequence, subsequent papers built on these results.

4.1.2 Paper B—Virtual Robustness Evaluations of Turbine Structure Assemblies Using 3D Scanner Data

Whereas Paper A addressed basic *assembly* variation, Paper B aimed at presenting a more quantitatively accurate way to address *part* variation. Still concerned with the T-sectors of TRSs, this paper used 3D scanner data as a way of realistically modelling the geometric variation in the T-sectors.

Some limitations in 3D scanning technology were identified. First, 3D scanning only captured non-occluded surfaces, thus only yielding information on a subset of the geometry. Secondly, the scanned geometry lacked information on abstract concepts of geometrical shape. A CAD model differentiates between spheres, cylinders, rectangles, splines, etc. A laser scanner returns objects as generic shapes defined by a set of data points, which implies that a laser-scanned model is not as easily parameterized as a CAD model. Therefore, a combined approach, where the scanned data points were used as a basis for a traditional CAD geometry generation, was suggested.

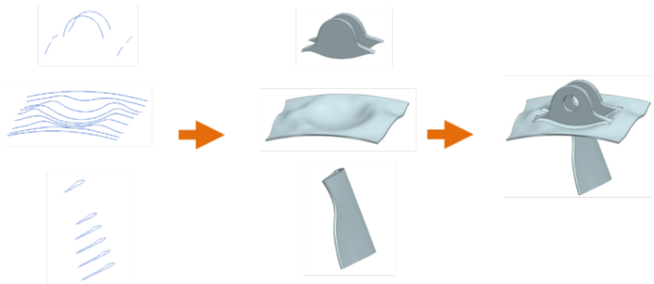

Figure 19: Generating the geometry from measurement data.

Figure 19 shows how the part geometries were generated. The geometry was interpolated from the design point parameters. These point parameters corresponded to certain points used in the original CAD generation. In this way, a parameterized CAD model, similar to the original model, could be obtained using the same design practices as in the original model. Spline interpolation was used to create curves from the points. The areas between these curves were then swept to generate surface models, which were subsequently uniformly thickened. This method yielded CAD geometries that were both geometrically and architecturally similar to traditional CAD models.

In order to alleviate the problem with stresses concentrating on non-continuous edges in Paper A, a tangential condition to create a smooth transition was set on welded edges. Still, this procedure was hardly a realistic depiction of the welding process, but the final result was nevertheless a fully connected assembly that represented a more realistic model.

To quantitatively analyse the effects of variation, five parts cast with different geometrical variation were virtually assembled into 25 geometries and analysed with respect to sixteen functional properties.

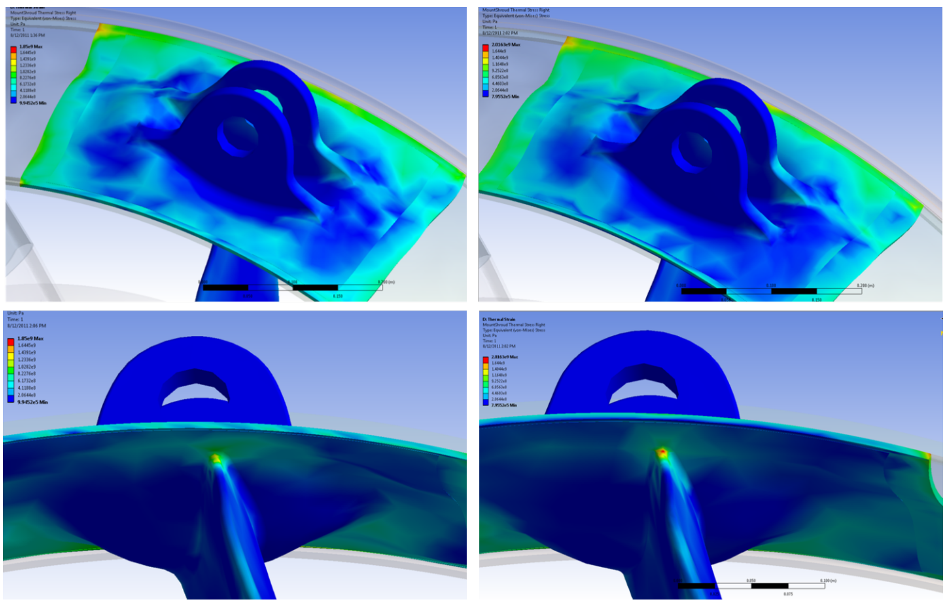

Figure 20: Thermal stresses, nominal and maximal, right mount shroud.

Figure 20 shows the results from the thermal stress simulation, comparing the results of the nominal geometry, with the one showing the maximum thermal stress. It was evident that most of the problems from Paper A, shown in Figure 18, were alleviated. The two-and three-fold increases disappeared. Instead, there was an 8% stress increase between the nominal (which is also the minimal) and the maximal case. For the nominal case, the max stress occurred in the far left corner, as shown in the top left. For the maximum case, the max stress occurred in the shroud-vane-blend. Owing to a combination of the elimination of sharp corners and less exaggerated applied variation, these results were more realistic that those presented in Paper A.

4.1.3 Paper C— Robust Lifecycle Optimization of Turbine Components Using Simulation Platforms

In Paper C, the methods from Papers A and B were combined. Paper A looked at assembly variation and Paper B at part variation. Whereas these two papers have been evaluative, Paper C investigated changing the reference points in a fixture assembly, as a means of suppressing the effects of part variation. In doing so, Paper C was the first paper to implement Taguchi's Parameter Design principles.

Paper C also placed geometric variation into a context by comparing its effects to other uncertainty. The paper looked specifically at computational error associated with physics decoupling and mesh resolution. The case study noted that the effects of geometric variation were partially obscured by meshing error. This paper was the first to discuss variation simulation against the framework put forth by Oberkampf *et al.* (2002).

Finally, Paper C presented a design automation tool enabling automatic generation of part geometries—something that had to be performed manually in Paper B. This procedure, which was accomplished through a C# script, allowed for industrial-scale non-nominal simulation.

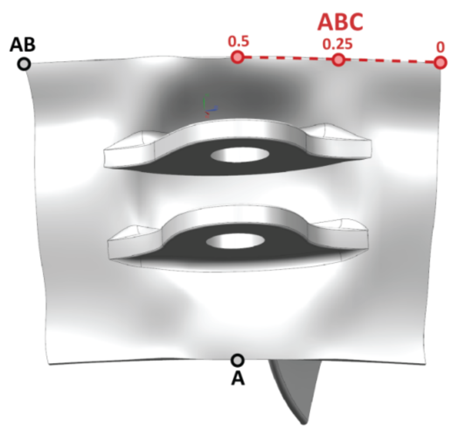

Figure 21: Part locating points.

In this simulation, a one-way fluid-structure interaction was modelled. In this case study, the effects of decoupling CFD and FE analyses were investigated. However, whether this small sample (20 scans) was representative of reality was subject to uncertainty.

A conversion from continuous to discrete mathematics is usually needed to calculate a numerical solution. The solution was thus approximate was fraught some error. The most apparent discretisation error was the PDE discretisation resulting from meshing. In the case study, the effect of mesh density was evaluated.

The simulation incorporated a one-way coupling between CFD and FEA simulations—the aero surface temperature provided the boundary condition for calculating material temperature and thermal stress. As previously mentioned, it is straightforward to realize that geometrical variation will affect structural strength. There will be another indirect effect as a change in the aero surface will affect the convective heat flow into the material, resulting in a different thermal expansion and expected fatigue life. This effect was evaluated by switching between boundary values from nominal geometries and scans as inputs to our FEA simulation. It was apparent that the thermal stress and centreline shift were mostly affected by the geometry change during the FEA phase. The temperature, however, was as affected by the thermal boundary conditions as the variation in structural geometry.

4.1.4 Paper D—Bridging the Gap between Point Cloud and CAD: A Method to Assess Form Error in Aero Structures

Paper D delved more deeply into the 3D scan-based methods put forth in Papers B and C. It introduced a new modelling approach that allowed for feature-based CAD geometries to be constructed from point clouds. The introduction of the modelling approach was presented against a framework of reverse engineering, specifically aimed at extracting higher level information from point clouds.

Varady's (Varady *et al.* 1997) hierarchy of surfaces is used to support the new modelling approach. This process consists of three steps:

1. **Segmentation**—the process of logically dividing the original point set into subsets, one for each natural surface, so that each subset only contains points sampled from a particular natural surface.
2. **Classification**—determining to which type of surface each subset of points belongs (e.g. planar, cylindrical).
3. **Fitting**—finding the surface of the given type that is the best fit to those points of the given subset.

Figure 22 illustrates a breakdown of boundary surfaces into a hierarchy.

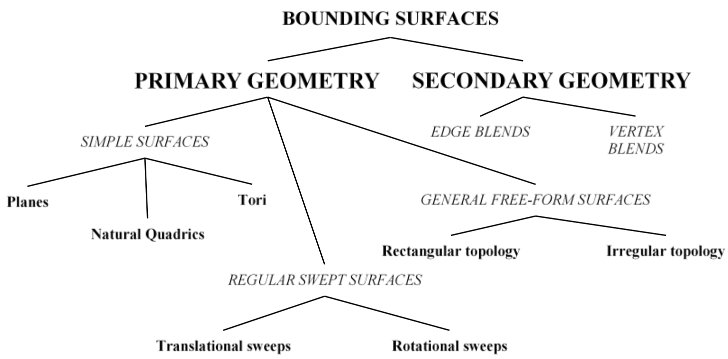

Figure 22: A hierarchy of surfaces (Varady *et al.* 1997).

Based on this framework, the new modelling approach was implemented on a TRS. Starting with a point cloud, a feature-based CAD-model was created in nine steps as shown in Figure 23. This method retained the parameters of CAD models while accounting for geometric variation in parts. In later papers, this methodology would be built upon further.

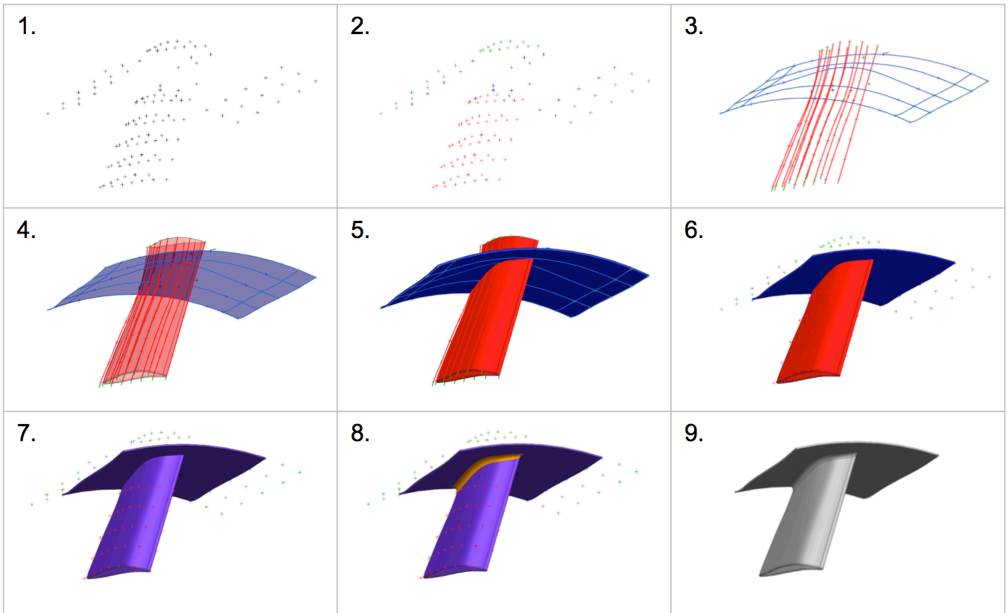

Figure 23: Generating a feature-based CAD model from point cloud data.

The new modelling approach also allowed more comprehensive analyses types. Whereas previous papers had limited their variation analysis to the mount lug T-sectors, the majority of sections were modelled nominally. In the new model, a full 360°-sector of eleven vanes, each representing different scans, could be generated. This possibility gave rise to new optimization problems. In particular, the configuration problem was presented of how to assemble eleven vanes with different variation characteristics in a way that minimized thermal stress, while maximising the expected fatigue life of the structure.

For a nominal geometry, setting up a simulation to examine these stresses was relatively straightforward. Since the eleven vane-shroud T-sectors were nominally identical, the problem was rotationally periodic, and only had one configuration. However, when form error was taken into account, each T-sector was different. As a consequence, each sector handled stresses and distributed loads differently. Being connected, the properties of each T-sector cannot be isolated from the next one. Hence, a simulation of the entire assembly must be performed for each simulation. Figure 24 illustrates this problem, using a variety of colours to represent different geometry variation.

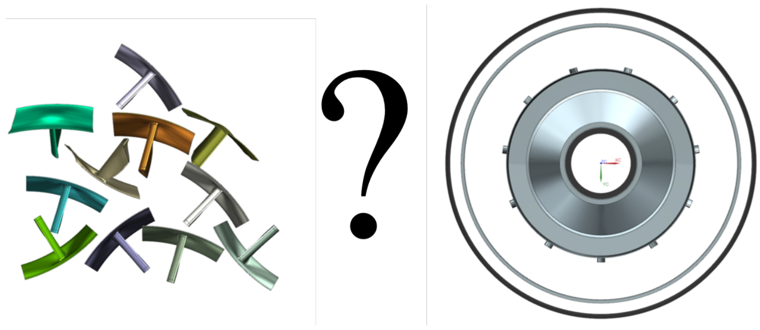

Figure 24: A combination problem.

To simplify this problem, the mount lugs have been omitted, so that the assembly contained eleven identical T-sectors. Because of axial symmetry of the loads, the orientation of the assembly became irrelevant. Hence, the problem could be reduced by using one T-sector to define a local coordinate system, which respect to which the other then parts would be positioned. Even so, the problem suffered from a combinatory explosion. There were 10! = 3,628,800 different configurations of this one product. To analyse every combination in a ten-minute simulation would take approximately seven years.

Therefore, a genetic permutation algorithm was implemented. The algorithm began by generating 100 random samples. Although this was just a fraction of the 10! or 3628800 possible combinations, it presented some knowledge of the effects of geometric variation on thermal stress and expected fatigue life. From there on, the algorithm generated 50 new samples for each generation, using a mutation probability $P_m=0.3$ and a crossover probability $P_c=0.4$. The simulation ended as the result converged, i.e. when there were fifty samples within some epsilon of each other.

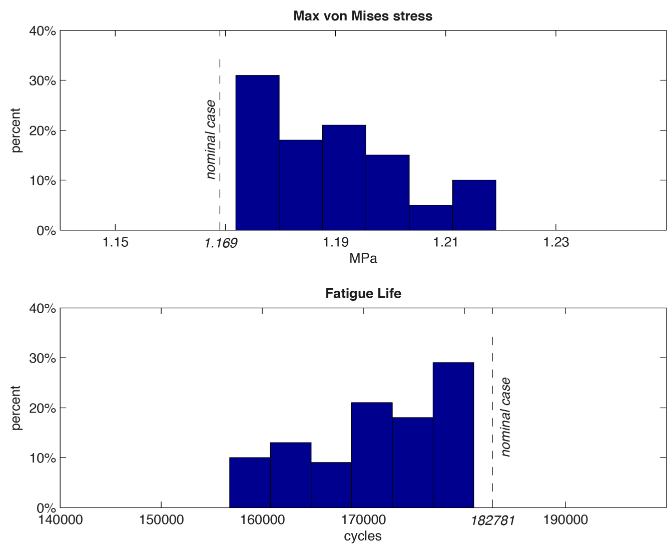

Figure 25: Initial Monte Carlo run.

Figure 25 shows a histogram of the results of the initial Monte Carlo simulation. These histograms show that any random combination of parts will likely increase thermal stresses and reduce fatigue life. For both characteristics, there is a performance decrease in the high single digits.

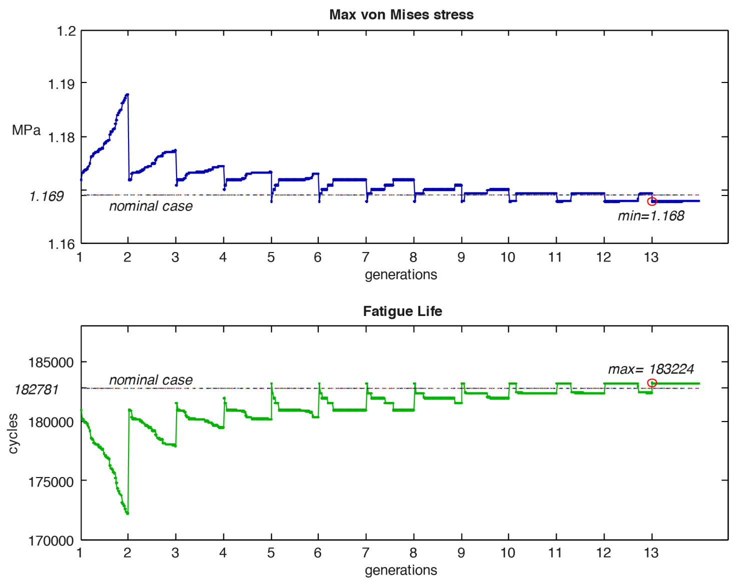

Figure 26: Genetic algorithm results.

Figure 26 shows the results of the genetic algorithm simulation. For each generation, current and previous generations of the top 50 candidates are shown. On the 13th generation, after five days of simulation, the results converged. In the initial phase, the top result for each generation was increasing. However, already by generation 5, an optimal result was found.

4.1.5 Paper E—Robust design of aero engine structures: Transferring form error data when mapping out design spaces for new turbine components

Whereas Paper D introduced a new method of creating feature-based geometries that could accommodate 3D scan deviation data, Paper E was the first paper that took advantage of these new possibilities. In Paper E, scan data collected from a larger TRS design was mapped onto a new, smaller TRS design. Fig. 27 shows the geometry from which the data was gathered on the left side, and the geometry to which the data was mapped on the right side.

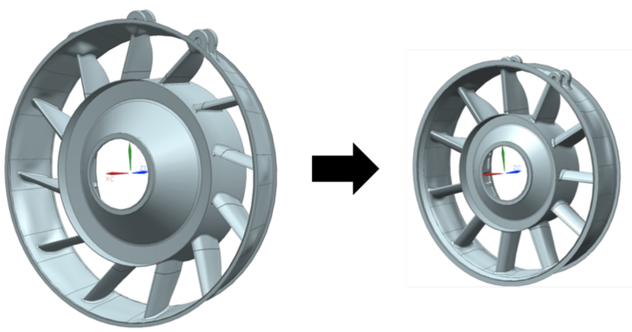

Fig. 27: Scan data obtained from a larger TRS could be mapped to a new design.

To further showcase the method, a design variable of the structure was allowed to vary. Fig. 28 shows the design variable selected—the blend between vane and shroud.

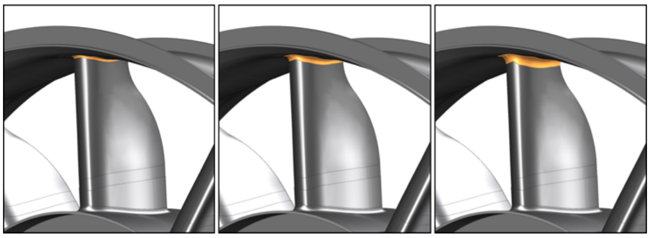

Fig. 28: Blend radius set to vary between 2.5mm and 10mm.

The radius of this blend was constrained to lie between 2.5mm and 10mm. As the results in Paper B had shown that thermal stresses tend to concentrate in this blend, particularly in the trailing edge, this is a region of interest to TRS design.

A genetic algorithm, similar to the algorithm introduced in Paper D, was implemented to find the optimal T-sector configuration of the new geometry. The algorithm was extended to include the shroud-vane blend as a design parameter.

Fig. 29 shows a scatterplot of all 500 design points over nine generations. The maximal stress recorded is 462.3 MPa, a 32% increase over the optimal value. Within the first few generations, the algorithm converges on a blend value at around 8 mm. In the vicinity of this value, stresses vary roughly 8%.

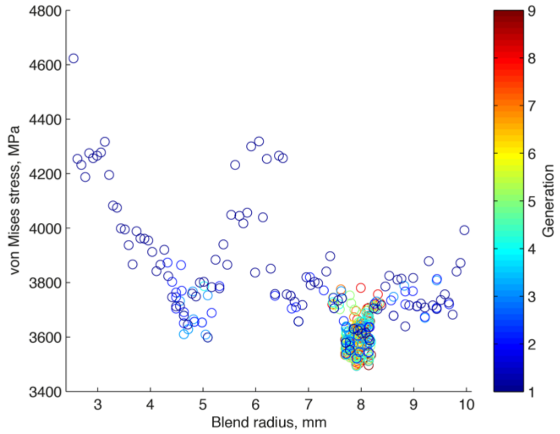

Fig. 29: Thermal stress as a function of blend radius.

4.1.6 Paper F— Evaluating How Functional Performance in Aerospace Components is Affected by Geometric Variation

Paper F built on the results in previous papers and presented a comprehensive synthesis based on previously published results. Paper F elaborated further on the general role of probabilistic analysis in modern simulation-based aerospace design.

The paper centred around the identification of four major barriers to implementing geometry assurance in industrial aerospace settings. These barriers were the following:

1. *Model form error*, i.e. the systematic errors and uncertainty that occlude variation effects when simulations are performed in different commercial off-the-shelf simulation environments.
2. *Discretisation error* and other software error, which limit the fidelity, veracity and validity of functional variation simulations.

3. *Backwards incompatibility*, which relates to the validity problem in new probabilistic approaches, as opposed to the heavily validated and established deterministic design practices in the aerospace industry.
4. *Forwards applicability*, which assesses the inherent limitation in requiring 3D-scanned manufactured goods to perform analyses, something that does not exist in the early design phases.

Paper F refined the modelling techniques developed in Papers D and E and proposed it as a methodology for overcoming the mentioned barriers. In this new context, the results from the previous papers were presented as applications.

4.1.7 Paper G— Fatigue Life Optimization of Welded Aerospace Structures Using Permutation Genetic Algorithms

Paper G built on the permutation genetic algorithm method introduced in Papers D and E, and presented a significant addition in the form of welding simulations. Whereas previous papers had identified the lack of welding simulation as a limitation, this paper was the first to include it.

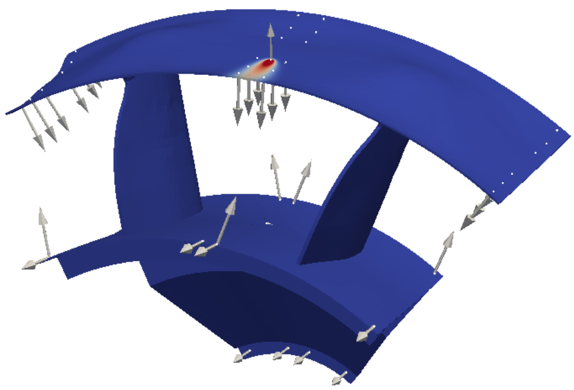

Figure 30: Welding simulation.

Welding is a process that in itself degrades material performance. However, when welded parts contain geometric variation the problem becomes much worse, since geometric variation causes parts to misalign with the consequence that fixturing force must be applied to realign them before welding. This process results in residual strain in the material and in an overall weaker weld.

This paper examined the welding of a TRS consisting of eleven T-sectors that were welded together. The welding process affected how well the finalized product would withstand thermal fatigue in flight. The repeated heating and cooling of an aero engine component in between flight cycles induce thermal stresses in the material, resulting in thermal low-cycle fatigue—a limiting factor in the service life of turbofan engines. When welded parts contain geometric variation, material performance is even further degraded as misaligned parts held in place by applying fixturing force make for weaker welds.

Although the ingoing parts were nominally identical, limitations in manufacturing caused each T-sector to exhibit dissimilar variation. When assembling these parts, certain combinations of parts would perform better. However, due to the many possible combinations of the eleven T-sectors, finding the optimal configuration can be difficult. The method presented in this paper suggested reconfiguring nominally identical T-sectors in a turbine structure assembly as a way of mitigating material fatigue. A two-step approach was presented. At the first stage, an exhaustive weld simulation was performed for each section pair. At the second stage, the pair-welding results were mapped to the eleven-vane structure and a thermal stress simulation was performed. A permutation genetic algorithm was then applied to the second stage to find the optimal combination.

The results showed that the fatigue life can be extended by more than a factor of three, from a median of 4,944 cycles for a random configuration to a fatigue life of 21879 cycles for the optimal result. An increase of this order is significant, especially taking into account that the only factor changed in the production is the configuration of these nominally identical T-sectors.

5 DISCUSSION

In this chapter, the research questions will be discussed and results achieved so far will be evaluated in terms of validation and verification.

5.1 ANSWERING THE RESEARCH QUESTIONS

Research Question I: What barriers to implementing geometry assurance practices can be identified in the aero engine industry?

Despite being widely understood to increase quality and reduce costs and lead times, the industrial implementation of probabilistic design practices in general and geometry assurance activities in particular, has been met with some resistance. Using the barriers to probabilistic work practices compiled by Zang *et al.* (2002), which were discussed in section 2.5, this research question aimed as a starting point to find the barriers to geometry assurance in particular. Although this question has to some extent been addressed by all papers in this thesis, Paper F answers this question most explicitly and comprehensively.

The barriers identified are the following:

1. *Model form error*, i.e. the systematic errors and uncertainty that occlude variation effects when simulations are performed in different commercial-off-the-shelf simulation environments.
2. *Discretisation error* and other software error, which limit the fidelity, veracity and validity of functional variation simulations.
3. *Backwards incompatibility*, which relates to the validity problem in new probabilistic approaches, as opposed to the heavily validated and established deterministic design practices in the aerospace industry.
4. *Forwards applicability*, which assesses the inherent limitation in requiring 3D-scanned manufactured goods to perform analyses, something that does not exist in early design phases.

These barriers were identified through a combination of literature review, interviews, and primarily, empirically from the case studies. The barriers have not been arranged in order of importance, nor do they provide an exhaustive list of all possible barriers. Barriers could potentially rank in the hundreds and include both quantitative and qualitative aspects, such as human averseness to change. However, all these barriers do not need to be overcome. Instead, the way forward is to address the most pressing barriers in order to reach a tipping point, where the benefits of geometry assurance outweigh the costs. Addressing the four barriers identified in this thesis provide a suitable starting point for tipping the scales.

Research Question II: How can geometry assurance methods be implemented in multidisciplinary simulations in industrial settings?

This research question addresses how the effects of geometrical uncertainty stemming from part and assembly variation can be evaluated in a multidisciplinary environment. Part of answering this question lies in overcoming the barriers identified in answering Research Question I.

Model form error constitutes a gap between the separate ecosystems used for quality control and mechanical simulations. The parametric point method, which was developed throughout Papers B to F, is a means of overcoming model form error. The methodology merges CAD based geometry definition tools and point cloud based quality control tools into a unified, multidisciplinary simulation environment. This process allows the mapping and representation of irregular deviations onto traditionally crafted CAD models. The process can be applied at an arbitrary level of fidelity, both with respect to the nominal geometry definition, as well as measured point cloud data. In doing so, this method eliminates comparative model form error effects. Paper F shows how the parametric point method can replicate traditional CAD geometries at an arbitrary fidelity by adjusting the density of the points.

The parametric point method is CAD based and the connected multidisciplinary simulation environment permits the use of different software for meshing and analysis. This procedure allows for code comparisons between meshing software, a method that can be used to verify and validate the meshing algorithms, as well as subsequent simulations.

Discretisation error is a barrier arising when turning a NURBS based geometry into a discrete mesh. It may include unacknowledged error, such as programming mistakes. Therefore, to assess mesh quality in COTS software, the engineer should both evaluate the effects of changing mesh initialisation parameters such as mesh density, as well as performing code-comparative analyses using different meshing software. The important metric to consider is whether the meshing idiosyncrasies of respective software affects simulation results.

To assess backwards incompatibility barriers when translating from deterministic to probabilistic design practices, the methodology has been devised to be software independent, to the largest extent possible making use of COTS software. The guideline is to use the software and methods already in use within industry, since they have already gone through extensive validation and testing. Further, in order to assess discretisation error and other software error, the methodology advocates creating software redundancies to allow for code-comparisons.

The issue of forward applicability addresses a Catch-22 in quality control; in order to avoid expensive design iterations, manufacturing issues need to be discovered during the early design phases. During these phases, manufacturing data, such as laser scans of cast geometries, are not available. Using the parametric point method, manufacturing data from previous products can be reused and transferred to new designs.

The parametric point method suggested in this paper assesses the problem of forward applicability by allowing design parameterisability, the method can be used for optimising individual design variables. However, design parameterisability can be utilised more radically. By changing design parameter dimensions such as inner and outer radii, and features such as vane count and lean angle, a single parametric point model can be made to represent substantially different product designs.

The papers included in this thesis have performed a plethora of structural, thermal and aerodynamic analyses while assessing both part and assembly variation. Table 4 categorizes the results from paper A-H with respects to the research questions answered, model and analysis types, parameters, uncertainty, and analysis domains.

Table 4: Quantitative metrics of papers A-G

	A	**B**	**C**	**D**	**E**	**F**	**G**
Research Questions							
I	x	x	x	x	x	x	x
II		x	x	x	x	x	x
III			x			x	
Model Type							
CAD based	x						
Point-cloud based		x	x	x	x	x	x
Analysis type							
Evaluation	x	x					
Optimization			x	x	x	x	x
Genetic Algorithms				x	x		x
Parameters							
Fixturing			x				
Model geometry					x	x	
Part configuration				x	x	x	x
Uncertainty Types:							
Part Variation	x		x	x	x	x	x
Assembly Variation		x	x				
Meshing Error			x			x	
Physics Decoupling			x				
Analysis domains							
Mass	x	x					
Temperature			x				
Thermal Stress	x	x	x	x	x	x	x
Centreline Shift	x	x				x	
Overturning Moment	x	x					
Shear Compliance	x	x					
Ultimate Stress	x	x					
Modal Analysis	x	x					
Aerodynamics		x	x			x	

Research Question III: What role should geometry assurance play in the early phases of aerospace component design?

A prerequisite for answering this question is that the effects of geometric variation on product functionality can be adequately quantified. Further, to assess the relevance of geometry assurance, the benefits of performing geometry assurance need to be balanced against the cost, complexity and computational intensity of the methods used. This research question aims at understanding geometric uncertainty in a broader context, i.e. the relative importance of geometry assurance against other product development activities.

The effects of geometric variation vary with the type of simulation. The domain where geometric variation has had the largest effect in within thermal stress simulation. Thermal stress is important because it causes material fatigue, which in turn is a limiting factor for the estimated service life of an engine component. From a simulation point of view, there is a major difference between thermal stress simulation and other simulation domains. Whereas structural characteristics such as centreline shift, overturning moment, and sheer compliance are determined by the behaviour of the structure as a whole, and aerodynamic characteristics are determined by averaging performance over outlet surfaces, whereas the thermal stress simulation evaluates the nodal extreme points of the geometry. This condition makes them more susceptible to the effects of geometric variation. Unlike results that average over large regions of geometry, where local variation will cancel each other out, in thermal simulations extreme, isolated deviations will define overall performance. It is also important to point out that because these simulations are only looking at extreme behaviour over a few nodes, they are significantly more sensitive to discretisation and software error.

It should be noted that the simulations presented do not use any hard data. CAD geometries, applied loads and the uncertainty magnitudes are not the same as the ones used in real development. In any case, the exact magnitude of geometric effects will inevitably vary with each test case.

According to Oberkampf *et al.* (2002), there are 24 different *categories* of uncertainty. Geometric variation is one of these categories. Although this thesis addressed mesh discretisation error and physics decoupling error in Papers C and F, most categories remain unaddressed. Although many of these uncertainty categories can be accommodated by the simulation approach, such as assessing the effects of material variation, other categories remain difficult to assess.

Papers C and F addressed the issue of mesh resolution and discretisation error as issues that have an undesirable effect on results. The effect of changing the mesh resolution was in the high single digits—the same order of magnitude as the effects of part variation. Although this finding underlined the importance of mesh quality, it also proved the converse point that failing to account for geometric variation in simulation adds an uncertainty of equal magnitude to a deficient mesh.

Commercial aircraft are perhaps the most complex products in the world, containing millions of parts and employing thousands of engineers in hundreds of different companies. Understanding all the uncertainty in such a process is impossible. However, not having all data at hand should not prevent the implementation of geometry assurance on aerospace component design. Instead, just by showing that geometric variation effects are of the same magnitude as those of mesh density, is sufficient to warrant the implementation of geometry assurance. In fact, this results suggest that the aerospace industry should allocate an equal amount of resources to account for each of these problems. Geometry assurance, like all probabilistic design practices, can be used as a tool for balancing simulation activities.

5.2 SCIENTIFIC AND INDUSTRIAL CONTRIBUTION

The principal scientific contribution of this research project is in identifying the role of robust design in general, and geometry assurance in particular, in the early phases of aerospace component design. Further, it fills in the theoretical knowledge gap between uncertainty quantification and geometry assurance.

The methodology proposed in this paper contributes to furthering academic understanding of the implementability of geometry assurance in multidisciplinary system design. Although this methodology focuses on relevance and usefulness in the aerospace industry, we believe these results can also be relevant to manufacturing industry in general.

For applied research, part of the objective challenge is to deliver results that are relevant and applicable to industrial needs and to avoid the ritual academic blind alleys described by Flyvbjerg (2006). Therefore, it was important that the results of this research did not end up in the “valley-of-death” between academia and industry. The use of COTS software and industrially established design practices, in addition to working closely with an aerospace component supplier, were elements whereby this risk could be mitigated. The resulting industrial contribution is a tool that is easy to implement industrially and that does not require a leap of faith from established deterministic design practices.

5.3 LIMITATIONS

The research presented in this paper aims at broad applicability within the aerospace industry. Through an extensive review of publications stemming from both academia and industries, the barriers identified and methods developed have been designed to be generally applicable and relevant. However, all case studies have been performed using one specific component (the TRS) at one industrial company. Further, only a portion of all simulation activities in the industrial product development of TRSs have been included in the work presented in this thesis.

Nevertheless, aerospace product development encompasses an ocean of engineering activities and to prove the applicability of any specific methodology for all these activities is hardly feasible for a single thesis. However, research is a collective process, and in the same way as this thesis builds on the work of others, the results presented can provide tools for others to build upon.

5.4 VERIFICATION AND VALIDATION

As mentioned previously, the research presented in this thesis contains qualitative and quantitative elements. The qualitative element is related to the descriptive study, the interviews and the decision to conduct case studies. The verification problem here is whether these interviews were properly conducted. The 32 semi-structured interviews provided a good foundation for the research. The interviews also served to validate the research as the people being interviewed were also the potential benefactors of the research. However, as the results from the interviews have not been printed in any scientific publication, there has so far been scant *verification by acceptance* from the academic community. From a *logical verification* perspective, the research is verified though the four steps of consistency, coherence, completeness and ability to explain phenomena.

The verification of the quantitative parts has been benefiting from the close collaboration with industry. The simulation methods used in industry have been put through extensive verification and validation procedures to comply with TRL standards and government regulations. The software used, as well as the methods employed, has to the largest extent possible been the same as those used in industry. However, concerns when using COTS software from a verification-and-validation perspective do have some merit. The problem with COTS software is that its source code is not open, essentially making it into a "black box". This problem makes it difficult to assess discretisation error and other programming mistakes with scientific rigour. Code-comparison is a practical method for assessing discrepancies between different COTS software. Although this method does not guarantee software accuracy, as the same error can be present in different software, it is often the only option when working with COTS software (Trucano *et al.* 2003).

Subjective verification, as suggested by Chen el al. (2004), has been used throughout this thesis. Chen et al. also suggest making quantitative comparisons of model predictions and reality. In an industrial context, this is an activity performed from TRL 7 and onwards, and the work presented in this thesis aims to range between TRL 3 and TRL 6.

This research used uncertainty quantification and the multidisciplinary simulation environment as methods to assess the relative importance of geometry assurance in early design phases. Uncertainty quantification is in itself viewed as tantamount to validation and verification of simulation methods (Oberkampf and Trucano 2008).

The barriers assessed in this paper are related to the verification, validation and scalability of probabilistic design practices with respect to their deterministic counterparts. The focus has been on the epistemic uncertainty and error related to simulation tools. For these purposes, deterministic design practices can be used as a benchmark. However, as noted in the introduction, deterministic design practices are inherently deficient in terms of assessing aleatory uncertainty quantitatively. This uncertainty includes geometric variation, but also uncertainty in operating conditions, as well as other boundary conditions and loads. Unfortunately, these verification-and-validation shortcomings are inherent in research at these TRLs.

5.5 FURTHER REMARKS

Two hundred years after the advent of mass production, high manufacturing tolerances still come at a high cost. Unlike computational power, which is continuously becoming less costly, the problem of geometric variation is not going away. Unlike software limitations in modelling and simulation, which are continually mitigated by software companies, geometric variation in manufacturing remains the sole responsibility of the manufacturing companies themselves. If a company does not take charge of controlling variation, it will be left behind.

Design practices and simulation tools are continuously evolving due to advances in computational capacity. In an industrial setting, change is the only constant. Therefore, methodologies developed should to the extent possible strive to decouple themselves from technological tools. The core activity of aerospace companies should be to understand their products and the underlying physics defining them. The computational tools themselves have no inherent value but are means to an end or even a necessary evil in order to allow designers to understand products.

Like all uncertainty quantification activities, geometry assurance is above all a learning tool for designers and engineers. It is an endeavour that exposes the limitations of engineering work and can at times seem overwhelming. However, these activities should not be undertaken with the mind-set of a perfectionist. When addressing uncertainty, a designer has to start somewhere. Doing something is always better than doing nothing. Failing to acknowledge geometrical variation will not make it disappear.

6 CONCLUSIONS

The research presented in this thesis has focused on the implementation of geometry assurance in aerospace system design. It has specifically addressed how to assess geometric variation on functional characteristics such as aerodynamic, thermal, and structural performance.

Research Question I aimed at identifying barriers standing in the way of successfully implementing geometry assurance in an industrial aerospace setting. When working in different simulation environments, one barrier is model form error. The discretisation and software error inherent in COTS software is another barrier affecting the fidelity of geometry assurance. Further, backwards incompatibility of probabilistic design practices is a barrier that compromises validity, as these practices lack validation through physical testing, which has lent credence to industrially established deterministic design methods. Lastly, the lack of quantitative manufacturing data in early design phases limits the forward applicability of geometry assurance.

Research Question II was answered by proposing a methodology to overcome these barriers. The methodology was designed to be applied in an industrial setting. Using COTS software to the largest extent possible, the methodology consists of a geometric modelling technique linked to a multidisciplinary simulation environment.

The modelling was based on the parametric point method, an approach that allowed point scanned data to be transferred to parameterised CAD models in a way that preserved design intent and provides forward applicability. This modelling approach was linked to a multidisciplinary simulation environment in order to perform the multitude of analyses needed to obtain statistically significant results in a complex engineering system.

In a series of case studies in the publications listed, the methodology was developed and refined in an industrial setting. The product under consideration was the turbine rear structure of a commercial turbofan engine, of which the system design process is dependent on aerodynamic, thermal and structural simulations.

The capability of the methodology was showcased trough applications in which CFD was used for aerodynamics simulation and FEA for structural and thermal analysis. Although geometric variation is shown to have an effect in all these applications, the most major impact occurred within thermal stress analysis. As thermal stress caused material fatigue and was a limiting factor in terms of product service life, these results underline the importance of geometry assurance in the early phases of product design.

In addition to the evaluative examples, three applications for optimising product design with respect to thermal stress have been outlined. These included optimising assembly fixtures, part configuration and isolated design parameters. These three examples highlight how the proposed methodology may actively contribute to reducing thermal stress.

Despite some limitations, the proposed methodology has proven successful in addressing the barriers. It virtually eliminated model form error and went a long way towards reducing both backwards incompatibility as well as forward applicability. In order to assess discretisation and modelling error, a software redundancy in the simulation environment was suggested, which allowed for code-comparisons to validate simulations when working with commercial off-the-shelf software.

Research Question III aimed at identifying the role of robust design in general, and geometry assurance in particular, in the early phases of aerospace component design. The case studies showed that simulation results were heavily affected by geometric variation in parts and assemblies. Such findings emphasized the fact that the effects of geometric variation must not be neglected in the early design phases.

Nevertheless, geometric variation needs to be placed in its proper context with respect to other uncertainty and errors. Simulation shortcomings, i.e. inadequate mesh quality, will partially occlude results of geometry assurance activities. Computer simulation is an activity composed of many phases, each interdependent of one another. In order to produce valid and reliable results, the uncertainty imposed during each of these phases need to be accounted for. In the case studies, the effects of mesh density were substantial, whereas the effects of physics decoupling were negligible. However, these results are not generalizable beyond the given context and uncertainty quantification activities must be repeated in every new setting.

The results of this thesis also showcased automated, multidisciplinary simulation environments as powerful tools for performing robustness analysis. Their advantage lied in that they sped up the design iteration loop, which simplified experiential design significantly. Combined with the theoretical framework of uncertainty quantification, the multidisciplinary simulation environment could not be used only to optimize the products themselves but also to optimize the product development process. By balancing the level of detail in all phases of simulation activity, an optimal allocation of resources and engineering time can be obtained. In summary, probabilistic design practices in general and geometry assurance in particular should be considered core activities of efficient product development.

6.1 FUTURE WORK

Future research may build upon the concepts explored in this thesis. Future work could include improving the quality and technological maturity of the multidisciplinary simulation environment, including its breadth as well its depth.

Perhaps most importantly in order to make this research more comprehensive, more researchers should be invited to contribute within their respective fields of expertise. Aerospace product development is a collaborative endeavour, and whereas the results presented in this thesis are the fruits of co-author collaboration, this aspect may be extended upon further. For instance, conducting this research in a collaborative framework of interconnected, parallel projects would more closely mimic the conditions prevalent in the aerospace industry. A collaborative approach could also address issues associated with inter-organizational product development, such as the sharing of sensitive data across company boundaries.

From a depth perspective, the quality of the simulation activities within the platform is a key issue. The weakest links of the simulation chain are currently those activities that stray from the established and validated industrial design practices. Currently, these tools and methods lie within TRL 3-6, and for widespread industrial implementation, they need to be further matured.

Figure 11 of chapter 2 lists 24 different *categories* of uncertainty. In this thesis, only three of these categories are addressed, only one exhaustively. However, the methods proposed in this thesis have the capability of addressing many other uncertainty.

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