THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

INCREASED PRECISION IN VARIATION SIMULATION BY CONSIDERING EFFECTS FROM TEMPERATURE AND HEAT

SAMUEL LORIN

CHALMERS

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
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Increased precision in variation simulation by considering effects from temperature and heat

SAMUEL LORIN
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Abstract

Every manufactured product deviates from the intended product. In a production series a number of noise sources will influence the product resulting in geometric variation. This variation leads to functional and aesthetical variation of the product. In geometry assurance, focus is on knowledge, methods, and tools to assure that the aesthetical and functional properties of a product are maintained for the non-nominal product. In this thesis, the effect of temperature and heat are considered in combination with variation.

The relative ease of the manufacturing techniques and their flexible physical properties has made plastics an attractive alternative to metals in many industries. However, the thermal expansion of plastics is often much larger than metal, and is often of the size of other effects considered in geometry assurance.

During assembly welding is a common joining technique. During welding a large amount of heat is induced into the welded assembly. It has previously been shown that welding deformations depend on positioning errors prior to welding. Therefore, in order to evaluate the robustness of an assembly that is welded; variation- and welding simulation need to be considered in combination. For this, methods and tools need to be developed.

In this thesis an interview study is performed that reports current issues and problems when simulating for robustness in plastic design. This led to a framework for descriptive studies for robust plastic design where part-, assembly and functional assembly are considered as different levels of robustness. This study influenced the focus of this thesis toward temperature and heat. A study on the combination of thermal expansion and variation showed that geometric variation is dependent on temperature. In order to evaluate the effect of variation in combination with thermal expansion a method and tool to simulate the distribution of stresses was developed. Including contact modeling in variation simulation considering thermal expansion was shown to lead to long simulation times in some instances. Therefore, a new contact modeling approach for variation simulation has been developed and shown to reduce simulation time significantly. A study focusing on rattle and squeak simulation showed that this is a further area where thermal expansion for the non-nominal geometry needs to be considered.

In order to enable variation simulation of welded assemblies, a method called the Steady state, Convex hull, Volumetric shrinkage-method (SCV-method) has been developed in a number of studies, giving reasonable results. Also, the influence of using clamps to reduce the effect of variation on weld induced deformation has been studied.

Keywords: Variation simulation, robust design, welding simulation, temperature, heat

Preface

In his novel ”The Pale King” late author David Foster Wallace describes one of his characters reflecting on the parked automobiles that he sees from the perspective of a descending airplane [Wallace, 2011]. He thinks about how, for each automobile, one person has parked the car, and for every car there are a number of persons who have assembled the automobile, and for every assembled car there are a number of persons who have thought about what car to build, and for every automobile there are many parts, and for every part there is a person responsible and perhaps a team that has been working on that part. One can add that every part needs to be designed so that the part is working with adjacent parts, that is, the parts need to be able to work functionally and aesthetical as a whole. Here, of course, are many sub-suppliers involved which requires working communication been them and the OEM. In addition to this, every automobile needs to be economically competitive on the market with all challenges that follow, from cost reduction in development and production to creating an attractive product for consumers. One can continue with observations of products that surround us all the time.

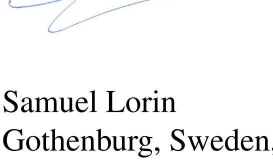
The thought is mind-boggling. Yet for me, as a person who has been involved in research in product development for the last five years, it does not stop here. For many products in today's market there are variants, to allow for personal preferences from the customers. Therefore, for every parts the product developer need to establish, not only one variant, but also how this part is allowed to vary, its *range*, and how this range will work together with the ranges from all other parts, i.e. its configuration rules. This variation is, however, sought in order to meet the assumed costumers preferences.

The topic of this dissertation deals, however, with undesired variation. For every physical realization of a product there are deviations from the intended product. In addition, the produced parts will vary from one another leading to products that vary from each other. Still, when the product is being assembled there is no time to find a particular part that will fit another specific part to enable assembly. Furthermore, the sought attributes of the product must persist even for the non-nominal product. Therefore, just as a designer needs to specify the geometry of the parts of a product he or she also needs to specify how the parts are allowed to deviate from the intended geometry. This is done using tolerances. In order to set correct tolerances the designer needs information of the accuracy of the manufacturing- and production system and what effect these tolerances have on all subsequent production steps and the final product. Tolerances are, furthermore, associated with a cost, hence it is important to find the right balance between quality attributes, tolerances, and cost. This is, in short terms, the problem in geometry assurance. Of course, this is not the first thesis on geometry assurance and it will not cover all these aspects.

In this thesis I will take a more focused view on some aspects during geometry assurance, often dealing with aspects concerning heat and varying temperatures.

One of the interesting aspects of doing research in product development is that it involves many facets. One facet consists of contact with industry; the quality of the research is often increased with the degree of involvement of people from the industry that contributes with interesting, albeit ”real” problems, meaning that they are not commodified to suit the specific inquire that for the moment happened to be in focus of interest. On the other hand, it can be a challenge to get people interested in testing applications in their industrial setting. Another facet regards the generation of theoretical constructs and the generation and implementation of ideas. Here, the academic partners have been indispensable. In this aspect I must mention how privileged I feel in working in such an inspiring environment as I have been doing for the last five years or so. First and foremost my thanks go out to my supervisor Rikard Söderberg. I admire your ability to realize your visions and I know that many of the components that have made this place such a fruitful and desirable research organization is a result from your leadership. You have been able to set up structures that have enabled natural meeting places for persons working within theoretical fields to persons working with real applications within industries. I think that my work has improved significantly by having the advantage of this vantage point that has enabled me to listen to-, and discuss, with an array of persons from different fields. However, you still have taken the time to discuss smaller and larger problems and have made me feel encourage from our interchanges.

I would, furthermore, like to thank Lars Lindkvist for all encouragement and discussions, Christoffer Cromvik for lending your time and knowledge and your humble attitude, Fredrik Edelvik for your support, Robert Sandboge for helping me raising my mathematical bar, Björn Lindau for the exchange of ideas and for being a good friend and Anders Ålund for always providing indispensable help with a smile. Warm thanks also goes out to Ola Wagersten, Christoffer Levandowsky, Anders Forslund, Marcel Michaelis, Karin Forslund, Casper Wickman and other persons working at PPU and FCC that I have interacted with.



Samuel Lorin
Gothenburg, Sweden, October 28, 2014

Publications

The following publications are included in this thesis:

Paper A
Lorin, S., Forslund, K., Söderberg, R., (2010), ”Investigating the role of simulation for robust plastic design”, *Proceedings of NordDesign 2010 International Conference on Methods and Tools for Product and Production Development*, August 25-27, Gothenburg, Sweden.

Paper B
Lorin, S., Lindkvist, L., Söderberg, R., Sandboge, R., (2013), ”Combining variation simulation with thermal expansion simulation for geometry assurance”, *Journal of Computing and Information Science in Engineering*, vol. 13, (3).

Also published in:
Lorin, S., Lindkvist, L., Söderberg, R., Sandboge, R., (2012), ”Combining variation simulation with thermal expansion for geometry assurance”, *Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE*, August 12-15, Chicago, IL, USA.

Paper C
Lorin, S., Lindkvist, L., Söderberg, R., (2014), ”Variation simulation of stresses using the method of influence coefficients”, *Journal of Computing and Information Science in Engineering*, vol. 14, (1).

Also published in:
Lorin, S., Lindkvist, L., Söderberg, R., (2013), ”Variation simulation of stresses using the method of influence coefficients”, *Proceedings of the ASME 2013 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE*, August 4-7, Portland, OR.

Paper D
Lorin, S., Cromvik, C., Edelvik, F., Lindkvist, L., Söderberg, R., (2014), ”Variation simulation of welded assemblies using a thermo-elastic finite element model”, *Journal of Computing and Information Science in Engineering*, vol. 14, (3).

Also published in:

Lorin, S., Cromvik, C., Edelvik, F., Lindkvist, L., Söderberg, R., (2013), ”Variation simulation of welded assemblies using a thermo-elastic finite element model”, *Proceedings of the ASME 2013 International Mechanical Engineering Congress & Exposition IMECE*, November 15-21, San Diego, California, USA.

Paper E
Lorin, S., Cromvik, C., Edelvik, F., Söderberg, R., ”Welding simulation of non-nominal structures with clamps”, *Accepted for publication in Journal of Computing and Information Science in Engineering*.

Also published in:
Lorin, S., Cromvik, C., Edelvik, F., Söderberg, R., (2014), ”Welding simulation of non-nominal structures with clamps”, *Proceedings of the 13th CIRP Conference on Computer Aided Tolerancing*, may 12-14, Hangzhou, China.

Paper F
Lorin, S., Cromvik, C., Edelvik, F., Lindkvist L., Söderberg, R., Wärmefjord K., (2014), ”Simulation of non-nominal welds by resolving the melted zone and its implication to variation simulation”, *Proceedings of the ASME 2014 International Design Engineering Technical Conferences* & *Computers and Information in Engineering Conference IDETC/CIE*, August 17-20, Buffalo, New York.

Paper G
Lorin, S., Cromvik, C., Edelvik, F., Lindkvist L., Söderberg, R., (2014), ”On the robustness of the volumetric shrinkage method in the context of variation simulation”, *Proceedings of the ASME 2014 International Mechanical Engineering Congress* & *Exposition IMECE*, November 14-20, Montreal, Quebec.

Paper H
Lindau, B., Lorin, S., Lindkvist L., Söderberg, R., ”Efficient contact modeling in non-rigid variation simulation”, *Submitted to Journal of Computing and Information Science in Engineering*.

Paper I
Wickman, C., Lorin, S., Weber, J., Lindkvist, L., Mannfolk, S., Nanda, A., Söderberg, R., ”Squeak and rattle simulation with consideration to temperature using E-

LINE^{TM} method and Monte Carlo based variation simulation", *Submitted to Journal of Integrated Computer-Aided Engineering*.

Additional publications

Lorin, S., Söderberg, R., Carlson, J. S., Edelvik, F., (2010), "Simulating geometrical variation in injection molding", *Proceedings of NordDesign 2010 International Conference on Methods and Tools for Product and Production Development*, August 25-27, Gothenburg, Sweden.

Lorin, S., Sandboge, R., (2012), "Stabilized finite element method for solids with large gradient mechanical properties", *Proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition*, November 9-15, Houston, TX.

Lorin, S., Lindkvist, L., Söderberg, R., (2012), "Simulating part and assembly variation for injection molded parts", *Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE*, August 12-15, Chicago, IL, USA.

Wärmefjord, K., Söderberg, R., Ottosson, P., Werke, M., Lorin, S., Lindkvist, L., Wandebäck, F., (2013), "Prediction of geometrical variation of forged and stamped parts for assembly variation simulation", *IDDRG 2013*, June 2-5, Switzerland.

Distribution of work

Paper A
Lorin and Forslund initiated the paper, performed the data collection and analysis and wrote the paper. Söderberg contributed as a reviewer.

Paper B
Lorin and Söderberg initiated the idea. The approach was implemented by Lorin with support from Lindkvist and Sandboge and the case study was performed by Lorin with support from Lindkvist and persons from the participating company. Lorin wrote the paper, Sandboge, Lindkvist, and Söderberg contributed as reviewers.

Paper C
Lorin initiated the idea. The method was implemented by Lorin and Lindkvist. The case study was performed by Lorin with support from Lindkvist and persons from the participating company. Lorin wrote the paper. Lindkvist, and Söderberg contributed as reviewers.

Paper D
Lorin, Söderberg and Cromvik initiated the idea. The method was implemented and simulations where performed by Cromvik and Lorin. Lorin and Cromvik wrote the paper with Edelvik, Lindkvist and Söderberg contributing as reviewers.

Paper E
Lorin, Söderberg and Cromvik initiated the idea. The approach was implemented by Cromvik and Lorin and simulations were performed by Lorin. Lorin and Cromvik wrote the paper with Edelvik and Söderberg contributing as reviewers.

Paper F
Söderberg, Wärmefjord, Lindkvist and Lorin initiated the idea. Lorin implemented the method and performed the simulations. Lorin wrote the paper with Cromvik, Edelvik, Lindkvist, Söderberg, and Wärmefjord contributing as reviewers.

Paper G
Cromvik and Lorin initiated the idea. Lorin and Cromvik implemented the method. Lorin performed the simulations. Lorin and Cromvik wrote the paper with Edelvik, Lindkvist and Söderberg contributing as reviewers.

Paper H
Lorin proposed to solve the contact problem as a quadratic programming problem. Lindau derived the exact formulation in relation to MIC. Lindkvist implemented the algorithm. Lindau and Lorin performed the simulations. Lindau and Lorin wrote the paper with Lindkvist and Söderberg contributing as reviewers.

Paper I
The idea was initiated by Wickman, Weber, and Söderberg as a master thesis project. The work was performed by Mannfolk and Nanda with Wickman, Lorin, Weber and Lindkvist as supervisors. Wickman and Lorin wrote the paper with Weber, Lindkvist, and Söderberg contributing as reviewers.

To Emelie and Alma with love

"*The scientist describes what is; the engineer creates what never was*."

Theodore Von Kármán (cited in [Mackay, 1991])

Contents

CHAPTER 1

Introduction

In every manufacturing situation there are variation. Hence, every part that is manufactured has variation in size and shape. The variations of the parts will lead to positioning errors when the parts are assembled to subassemblies or products. Here, additional variation is introduced from non-nominal fixturing, variation in assembly process parameters, variation in the environment such as the temperature and air humidity of the plant, and additional human errors. Therefore, one of the challenges in mass production is how to design products so that they can be assembled according the production plan and that the desired properties of the assembled product are assured. These properties can include both functional and aesthetical aspects thereby influence the product experience of the consumer. Hence, variation influences both the time and cost to bring a product to the market and the quality of the final product. Because of this, the management of variation is, in many industries, of crucial importance, and has been identified as such [Söderberg et al., 2006].

The management of variation can be divided into requirements and tolerances. Requirements are the designers limits on the quality features of the product and tolerances are the limits between which a specific dimension can vary so that the final product is within its requirements. Tolerance management is sometimes described as a critical link between the designer and the manufacturer [Chase et al., 1998], see Figure 1.1. This figure illustrates that from the perspective of the designer, tight tolerances are preferable. Tight tolerances require less nominal gaps between adjacent parts, and both function and aesthetics can be enhanced by requiring near nominal products. On the other hand, from the perspective of the manufacturer tight tolerances lead to increased manufacturing cost, increased assembly time, higher scrap rates etc. In order to ensure the design intent, fit and function while ensuring economically feasible and manufacturable assembly, designers need to know the relation between feasible tolerances and the cost associated with these tolerances, and to be able to predict their consequences on the

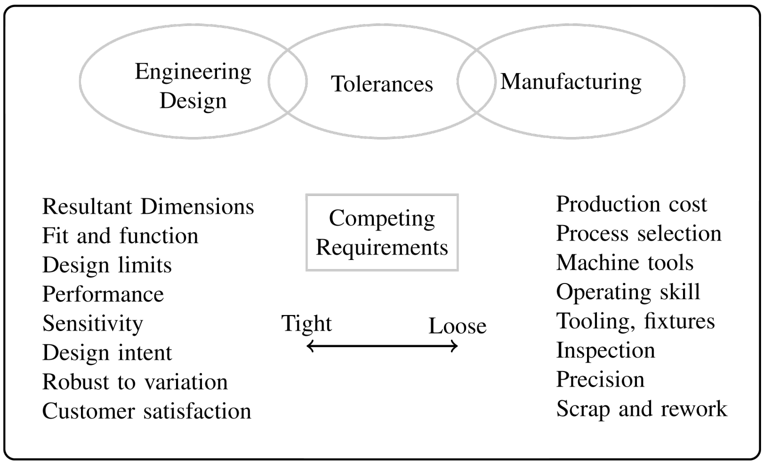


Figure 1.1: Tolerances can be seen as a link between engineering design and manufacturing [Chase et al., 1998].

product and use of the product.

In the earlier phases of product development large emphasis is on virtual product development. The primary reason for this is to avoid the high cost associated with the creation of physical prototypes. By predicting product properties in the earlier design phase where the cost of design changes is low, it is possible to avoid design changes in later stages when the time, cost, and effort for a design alteration is much larger [Ullman, 1992]. Furthermore, using virtual tools it is possible to compare a set of design concepts, to investigate effects of a design change, and use optimization techniques to find optimal settings for design parameters. Of course, the inferences and conclusion drawn using a virtual model is dependent on that all relevant phenomena is identified and can be properly modeled and the accuracy of the specific simulation model.

In the next three sections an overview will be given on how to work with the management of variation. This is to provide the framework onto which the research gap and research questions will be identified and positioned.

1.1 Geometry assurance and robust design

Ullman describes improvements in product development generally as reduction of cost, reduction of time to market and improved ability to meet customer demand [Ullman, 1992] [1]. As described in the previous section, the management of variation influences all these aspects. Geometry assurance is a framework of activities aiming to reduce the effect of variation, i.e. to increase the precision of functional and aesthetical attributes of products in the concept, verification and production phase, see Figure 1.2. The work presented in this thesis is aimed at the activities in the earlier stages of the product development loop.

The sources of variation are many and it is often the case that it is both difficult and expensive to reduce them. In Robust Design, instead of finding means to reduce the sources of variation, the aim is a design with properties that are not sensitive to variation, since adjusting design parameters towards a robust solution *can* often be done at low cost.

To take a simple example, consider recipes for two different cakes; if it is of vital importance that all ingredients are in their right proportion to the gram, and the time in the oven needs to be within the precision of seconds, the recipe is *sensitive*. On the other hand, a recipe for which it is possible to improvise the proportions of the ingredients and the time required in the oven, is considered *robust*. Of course, it might be that the former cake example is much more attractive than the second cake example for other reasons. A more detailed introduction to robust design and geometry assurance is given in Section 2.3 and 2.5.

1.2 Locating schemes

A locating scheme is a description of how the parts are positioned to other parts in the product, to fixtures during assembly or during inspection. The locating scheme is one of the most important factors for how the variation of size and form of the parts will spread throughout the product [Söderberg and Lindkvist, 1999]. Hence, it is important to consider the locating scheme during design. Previous research has led to methods for optimizing the locating schemes for a robust assembly, see [Camelio et al., 2002] and [Lööf, 2010]. However, in most practical application there are competing demands and restrictions on where to place interfacing surfaces between parts. It is, therefore, important to have several means of finding a robust design solution [Lorin, 2010].

The position in space of a rigid object can be specified by the position, (x,y,z), of one point of the body and three linearly independent rotations (φ,θ,ψ), in relation to a reference configuration. This is, a rigid part has 6 degrees of freedom. A locating scheme for an object consists of a description of where the object is fixated in a specific direction. In Figure 1.2 a $3-2-1$-positioning is shown.

[1] In addition to this, perhaps one might add an increased ability to influence the customer demand.

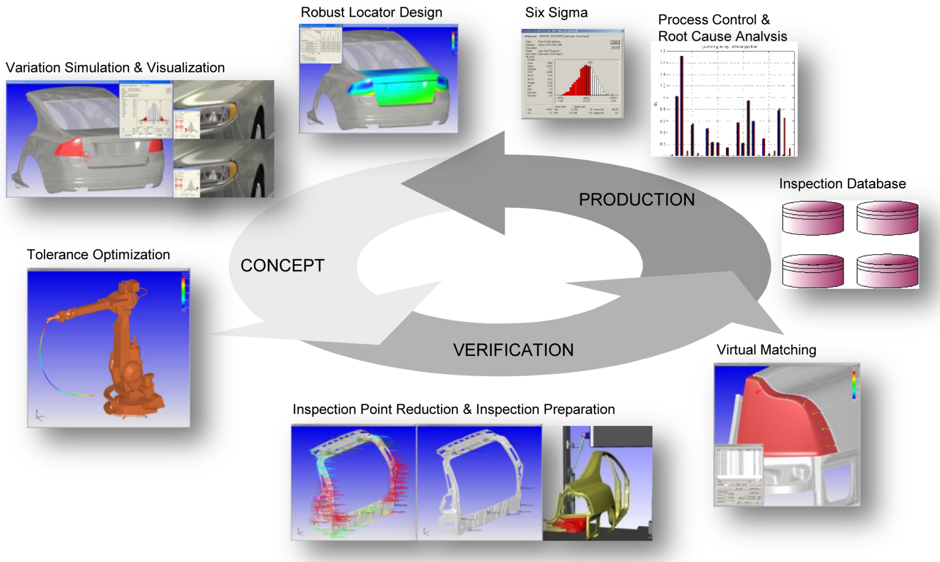


Figure 1.2: The framework of Geometry assurance consisting of a set of activities throughout the product realization process aiming at reducing the effect of geometric variation [Söderberg et al., 2006].

This is a common locating scheme for rigid parts[2]. Here, 3 ”A”-points are used to form a plane on which the object will be constrained. When the positioning points are brought into contact with their mating points the object will be locked from translation in the z-direction and rotation around the x- and y-direction. 2 ”B”-points are used to define a line along which the object is constrained to move. These points will lock the object from translation in the y-direction and rotation around the z-direction. The final degree of freedom, translation in the x-direction, is locked by a ”C”-point. Here, any deviation from nominal in the locking direction in the positioning point, in the part or mating point in the fixture will lead to a rigid body transformation of the object.

For an assembly where parts are able to deform during assembly, it is possible to add additional constraints, i.e. to over-constrain the part. This is done to compensate for gravitational effects or variation in parts and fixtures. A more detailed overview of locating schemes is given in Section 2.5.2.

[2]Here ”rigid part” denotes a part that can be considered rigid during assembly.

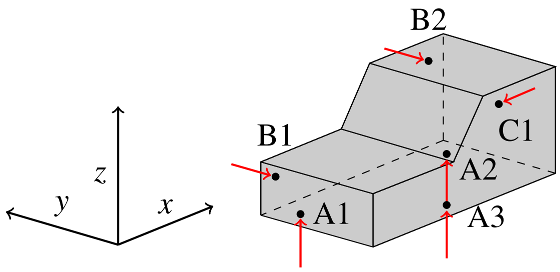


Figure 1.3: A 3-2-1 positioning system.

1.3 Variation simulation

The critical link between requirement and tolerances in virtual product development is *variation simulation*. Variation simulation makes it possible to predict the consequence of a set of tolerances on critical measures in order to evaluate key characteristics of the product.

In rigid variation simulation the locating scheme together with tolerances of the parts and fixture work as input to calculate the translation and rotation of all parts in the assembly in order to predict geometric variation of critical measures. There are several methods available to do this, as will be described in Chapter 2. In non-rigid variation simulation, the simulation of part deformation needs to be included. This is often based on the Finite Element Method (FEM). A more elaborate introduction of variation simulation can be found in Section 2.5 and 2.6.

1.4 Research focus and hypothesis

During the work resulting in this thesis the research goal has evolved. In effect, some of the results presented in this thesis have contributed to the clarification of the research agenda of the thesis, while other results are more focused on addressing the agenda. The scope of the research project was initially more generally on geometry assurance for plastics. Therefore, in one of the appended papers, Paper A, the research focus is more generally on plastics. One of the outcomes of this study was the need for knowledge, methods and tools regarding the effect of temperature on non-nominal products. During the project, the effect from temperature and heat evolved into the main focus.

The focus of the research presented in this thesis is on identifying phenomena, related to temperature and heat, that is contributing to the effect of variation and developing methods and tools to enable virtual evaluations of non-nominal assemblies concerning these phenomena for the industrial design context. The general hypothesis is that robustness evaluation needs to be considered in combination with effects from temperature and heat in the product life-cycle.

Previous research in geometry assurance usually does not consider the effect of heat during the assembly process or the effect of temperature during the user phase of the product. Instead, virtual evaluations of phenomena involving heat and temperature are usually done under nominal conditions only. Hence, any combinatoric phenomena of variation and temperature and heat will be missed. The result of this is that some quality issues for the product in the user's phase will be missed, or, products are designed to allow for being exposed to temperature spans without proper knowledge on which to base design decisions.

One of the most common joining techniques during assembly is welding. Here, the large amount of heat will cause the assembly to deform. In welding simulation, previous research has shown that welding deformation is dependent on positioning errors [Pahkamaa et al., 2012]. Here, however, the large simulation times makes variation simulation unfeasible for the industrial context. Here, knowledge and methods on how to evaluate the robustness of assemblies are needed.

1.4.1 Scientific goal

Research in product development is motivated by, seen or anticipated, challenges from an industrial context. The scientific and industrial goal might, therefore, have some overlap. The more scientific goal is to provide knowledge about the challenges related to quality- or the process of assuring quality of products, when considering temperature and heat. Also, with knowledge of these challenges, methods and tools are developed and evaluated with the aim to increase the quality of products.

1.4.2 Industrial goal

The primary industrial goal is to create an awareness of the quality issues related to temperature and heat and to provide means for addressing them in the design process.

1.5 Research questions

With these goals in mind, the following research questions have been posed to guide the research in this thesis:

Research question 1: In product development, what are the non-nominal quality aspects, affected by temperature and heat, which need to be addressed?

One prerequisite in doing research on product development is an understanding of the situation at hand. In researching this question, the goal is to understand the issues and problems faced by industrial practitioners. The results are put into relation to existing literature on related topics.

Research question 2: What are the challenges, during product development, in assuring product quality with regard to temperature and heat?

RQ 2 addresses the questions and challenges of assuring the quality of products, for phenomena that are known. RQ 2 and RQ 1 can sometimes be addressed jointly. In developing a strategy or method that enables the evaluation of a certain phenomenon, an implementation and evaluation of a case study can shed light on aspects that need to be addressed.

Research question 3: How can product quality be evaluated including effects from temperature and heat?

Development and implementation of methods developed to address the challenges identified can, further, give increased knowledge on how to improve the process of product design.

1.6 Delimitation

During this research project, several areas have been covered. Therefore, different limitations are applied to the research questions.

- RQ 1 and 2: The industrial perspective comes mainly from challenges from automotive- and aerospace industry together with industries supporting them.
- RQ 3: For the appended papers dealing with thermal expansion and contact modeling, the assumption is that part variation is small compared to the dimension of the part, linear FEM is used, i.e. it is assumed that the deformations are small so that infinitesimal elastic theory can be employed and that a linear material model is valid.

  Due to the limitation in RQ 1 and RQ 2, the focus on heat has been in the application of assembly process of welding considering variation stemming from positioning errors. During welding there are a number of additional sources that can potentially contribute to geometric variation of the assembled product. These include variation in the heat and effect of the weld gun, variation of the distribution of filler material, and variation in material properties due to impurities. These have not been considered in this project. However, as the field of non-nominal welding simulation gains a higher degree of maturity, it is of interest to consider these factors in robustness evaluations.

1.7 About the research project

This research project has been carried out within the research group ”Geometry Assurance and Robust Design” of the Wingquist Laboratory VINN Excellent Centre within the Area of Advance - Production at Chalmers university of technology. Within this group research focus is on decreasing the effect of variation throughout all stages of the product realization, see Figure 1.2. With reference to this figure, the main contribution in this thesis is mainly directed to the early activities in the product development process, when design concepts are mature enough to draw conclusions from simulation but there is still room for design changes, see [Wagersten et al., 2011].

1.8 Outline of the thesis

This thesis is based on research that can be divided into 2 parts. The first part springs out of the project ”Variation Simulation for Light Weight Assemblies”. The goal of this project is to generate knew knowledge, tools, and methods to perform variation simulation for light weight assemblies including plastic and rubber parts. The second parts springs from previous research on the combination of variation simulation and welding simulation which was shown to be non-additive [Pahkamaa et al., 2012].

Part 1 and part 2 both deal with the mechanical response to temperature and heat. However, in the first part the main focus has been on geometry assurance of the product during the user phase. Here the temperature is considered static. In contrast, in part 2, the focus is the production phase where the heat induced from the weld gun creates a transient temperature field and the large temperature fluctuations lead to phase transitions of the material.

The thesis is structured as following;

Chapter 1: In this chapter an introduction is given to the topic and main concepts used in this research. Also, the research gap and research questions are introduced.

Chapter 2: The research areas involved in this research are introduced in order to position it against existing theories and methods.

Chapter 3: This chapter is devoted to the research approach and methodology used.

Chapter 4: Here the research results are presented.

Chapter 5: The research results are discussed in connection to research questions and research quality measures.

Chapter 6: Conclusions and future work are addressed.

Acronymes

MLS	Master Locating System
MC-method	Monte Carlo-Method
MIC	Method of Influence Coefficients
SCV-method	Steady state, Convex hull, Volumetric shrinkage method
FEM	Finite Element method

CHAPTER 2

Frame of Reference

In this chapter an overview of the research fields connected to this research will be given. As described in the previous chapter, this work can be positioned within the framework of geometry assurance. The aim of geometry assurance is to assure the geometric quality of products. Therefore, this chapter starts with a description of quality by introducing intended functions and appearances and quality loss. The geometric quality of a physical product is closely connected to the robustness of the design. Therefore, robust design is addressed next. In relation to geometric robustness, one of the most important factors is how parts are positioned in space, during assembly operations or toward adjacent parts. This is addressed under locating schemes. The geometric outcome is also dependent on what tolerances are assigned to parts and subassemblies. To analyze tolerances statistics and probability analysis will be used. Furthermore, to predict the propagation of tolerances throughout the product, kinematic and structural relations need to be analyzed. In some of the appended papers optimization is used, therefore a short introduction to optimization will be given. In the common assembly technique of welding, high amount of heat is affecting the geometry. Therefore, in this research a focus has been on robustness evaluation of welded assemblies. An introduction to welding and welding computations will thus be given. Finally, a discussion of quality in simulation will be given.

2.1 Intended functions and appearances

In order to position variation simulation and robust design, it can be useful to expand upon the significance of deviations from the intended functions and design. This is intended to shed light on the problem of design, in connection to geometry, and not to be a description of how this work is actually done.

Product requirements have been compared to Maslow's hierarchy of needs

[Maslow et al., 1970, Yalch and Brunel, 1996, Crilly et al., 2004]. The more fundamental needs of a product are; intended functions, utility, safety and comfort. Once the more basic needs are met, focus can be tilted towards the subjective experience of the product. Here, product design can be seen as communication [Monö et al., 1997, Crilly et al., 2004, Crilly et al., 2008, Forslund and Söderberg, 2009], see Figure 4.1; there is an intent, on how to experience the product that is viewed as a transmitter. Here, the environment, working as a channel, is taken to mean the physical conditions for the properties of the product in the environment within the interaction between the product and the consumer.

However, there are disturbances that can affect how the designers intent is mediated to the customer. Firstly, the designer needs to consider constraint to enable the production and function of the product, as well as legal, financial and organisational constraints [Crilly et al., 2008]. Here, typically a large amount of engineering work needs to be devoted to assure that, for example, the parts need to have a geometry that enables their intended manufacturing process, there might be situations were some deviations are preferred over others (a pin can be smaller than its corresponding hole, or slot, but not the other way around), or the products may need to have room for cables etc. Because of this, the designed geometry of the parts, and the product is often different from the intended product. These are referred to as the nominal part respectively the nominal product. Secondly, the manufacturing- or production process will have an impact on the product; i.e. there are deviations from the nominal product. Examples are sink marks on parts manufactured through the process of injection molding, or weld induced distortion. Thirdly, there will be environmental noise in the manufacture- and production process that will lead to geometric variation of the final product. Fourthly, the product will be subjected to age and wear. This is called intent distortion and is schematically depicted in Figure 2.2. In addition, the final product will be used in a range of environmental conditions, including varying heat and humidity as well as viewed in varying light etc., hence, the designer needs to assure that the product conveys the same design intent during these conditions. Finally, in interaction with the product, the consumer will receive phenomena and create an experiential response.

2.2 Quality loss

The aim in geometry assurance is to reduce the effect of variation in order to increase product quality. Instead of defining quality, Taguchi et al. focus on the *quality loss* as a measure of "the loss imparted by the product to the society from the time the product is shipped" [Taguchi et al., 1989]. Hence, these authors stress that what is important with the term *quality* is the effect caused by an imperfect

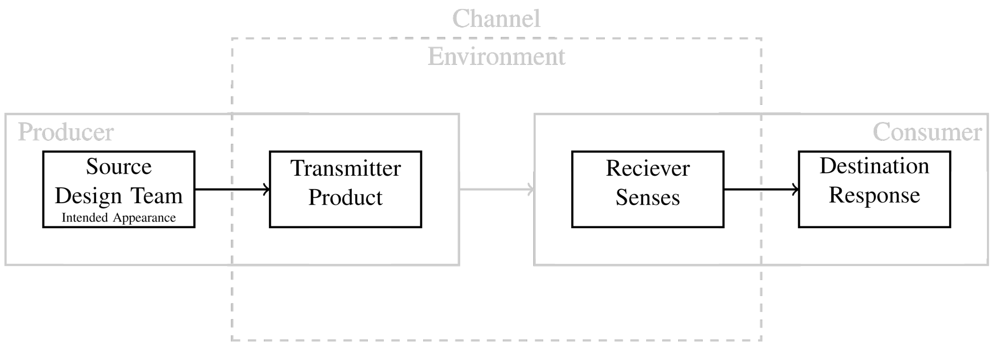


Figure 2.1: Product design as communication [Monö et al., 1997].

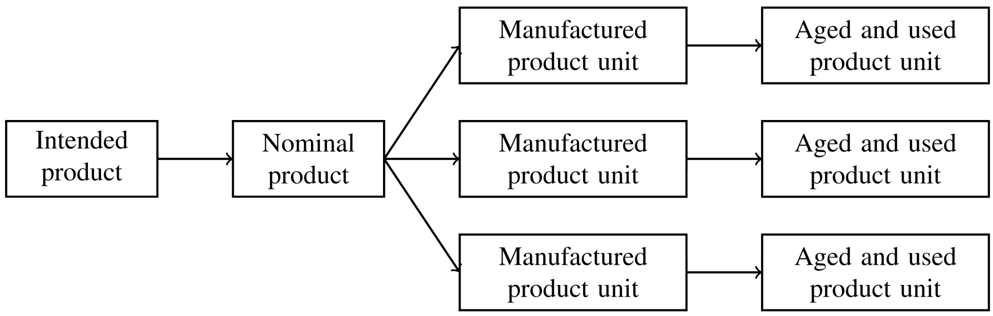


Figure 2.2: Distortion of the design intent [Forslund and Söderberg, 2009].

product. This definition can be expanded to include also loss during the production of the product. Quality loss can be due to, for example, extra assembly-time caused by non-nominal parts in the factory, additional CO_2 emission as a result of transportation of necessary spare parts, products that are not attractive due to imperfect production, as well as other aspects of the non-nominal product. Of course, it may not be practically possible to define this quality loss in any accurate way but it may guide and enable the comparison of different alternatives. In quality engineering it is therefore common to define a quality loss function to describe the loss of quality due to a product measure, y, deviating from the nominal dimension T

$$L(y) = f(y - T). \tag{2.1}$$

Many such quality functions have been proposed and this idea is not generally new [Nair et al., 1992]. One strategy is to apply a cost for every measure outside of tolerance. That would result in a quality loss function that is depicted in Figure 2.3(a). Taguchi et al. [Taguchi et al., 1989] emphasized that there are costs associated to products that deviate from nominal, but are within tolerance. They suggested instead a quadratic quality loss function, see Figure 2.3(b). This quality loss represents costs that are associated with quality branding, increased repair cost, increased assembly-time, etc. In figures 2.3(a) and 2.3(b) it is assumed that the quality loss obtain it's minimum at the nominal value, i.e. Nominal-the-best. There are quality loss functions that are smaller-the-better, larger-the-better [Phadke, 1995] or asymmetric [Söderberg, 1994b, Söderberg, 1994a] and [Phadke, 1995] that are applicable to different situations, see [Phadke, 1995] for an overview. In this thesis, it is assumed that the quality loss is of Nominal-the-best type, if nothing else is indicated.

2.3 Robust design

It is often difficult or expensive to diminish the sources of variation. The aim in *Robust Design* is a design that is not sensitive to noise, i.e. it is the effect of variation, not the source, that is to be minimized. The beginning of the modern subject of robust design is often accredited to the work of Genichi Taguchi. Taguchi developed both a philosophical framework of quality, see Section 2.2, as well as a number of statistical methods to be used in finding robust solutions, see [Nair and Shoemaker, 1990, Nair et al., 1992].

Robust design is a methodology with the goal to, instead of gaining an understanding of a system, economically find robust design solutions [Nair et al., 1992]. And, although Taguchi made a large contribution to robust design, the idea of trying to reduce sensitivity to noise has a much longer history, see for example the paper by Morrison, where he stresses the importance of considering the manufacturing variance in engineering design [Morrison, 1957] and Michaels' paper about experimental design [Michaels, 1964].

Robust design can be illustrated as a system [Phadke, 1995], see Figure 2.4. The system has *input*; it performs transformation of the signal, and it has intended *output*. In addition, there are factors that influence the transformation. These factors are categorized as *control factors* and *noise factors*, where noise factors are the factors, which are expensive or difficult to control. Using this illustration, the problem in robust design is to find the settings of the control factors, that minimize the influence from the noise factors. If this is successful, the effect of variation can be reduced without having to resort to reducing the source of variation. However, which strategy to take is dependent on the situation at hand. In Figure 2.5, this procedure is illustrated using the graph of a function. The nominal value of the input signal is here considered the control factor and the variation of the input signal is considered a noise factor. By increasing the nominal settings of the input

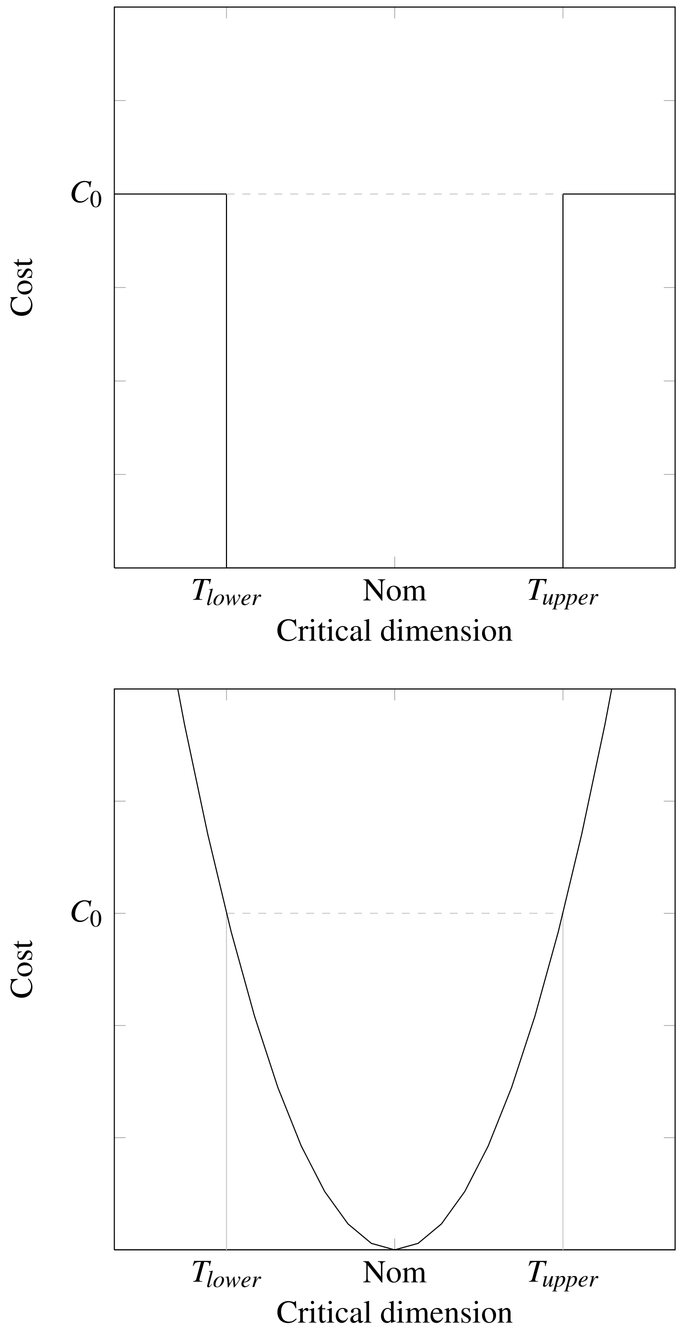


Figure 2.3: Quality loss functions. Above, a step function and below a quadratic function. C_0 is the cost associated with the quality loss at the requirement limit.

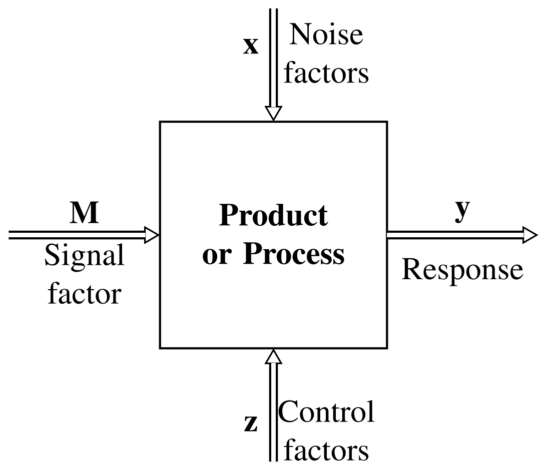


Figure 2.4: Robust design as a system.

parameter the variation of the output signal is decreased, without decreasing the input variation.

The noise factors can further be classified, according to Phadke [Phadke, 1995], into;

1. **External**; the environmental condition and loads that the product is exposed to when in use.

2. **Unit to unit**; the variation springing from the variation in the manufacturing process and assembly situation.

3. **Deterioration**; the drift in time from the intended function as the product deteriorates.

In this thesis it is only noise associated with noise classes 1 and 2 that is considered.

In the context of geometry assurance, the intended product is identified as the input and the consumer experience as output. The control are identified as locating schemes, nominal manufacturing settings, materials, color schemes etc. The noise factors, finally, is variation in the process parameters in the manufacturing of the part, variation in the material properties, variation springing from tooling and assembling, environmental variety within which the product is used etc.

Phadke, furthermore, proposes three stages in finding a robust design [Phadke, 1995];

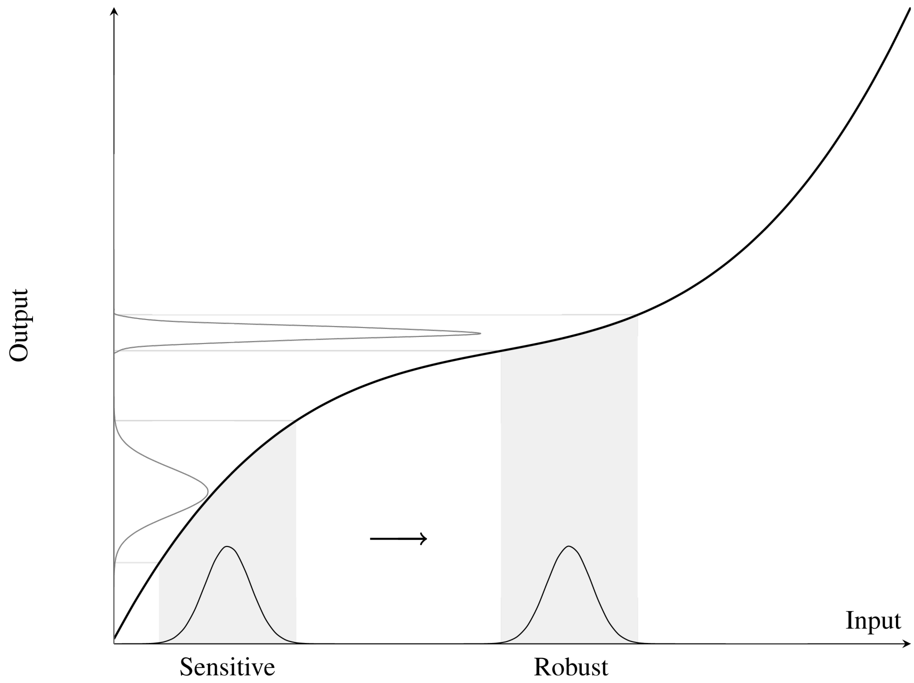


Figure 2.5: Robust design illustrated using a 1−dimensional function.

- **Concept Design**; in the early product development phase, the designer produces several options that fulfill the intended design. These designs are evaluated and compared to each other.

- **Parameter Design**; in parameter design, different analysis and optimization techniques are performed to find the optimal settings for the control parameters.

- **Tolerance Design**; Here, the goal is to allocate the tolerances in an optimal way with consideration taken as to the cost associated with tolerances and geometric variation.

Robust design has received some critique over the years. One form of critique comes from the statistics community. John Nelder argues, for example, in [Nair et al., 1992] that robust design, as put forward by Taguchi, tends to formalize the analysis work in such a way that important information is not used. Furthermore, Mayers and Vining in the same publication state that, although they recognize that Taguchi has brought attention to statistical methods to the industry, it ”will take time before parameter design is adopted at the level that professional statisticians would like” [Nair et al., 1992].

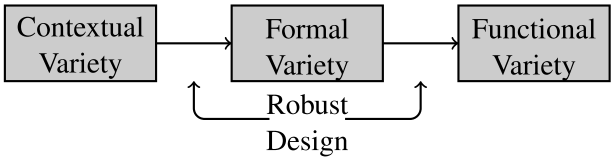


Figure 2.6: Robust design as an activity to break the linkage between contextual-, to formal- and from formal to functional variety [Smith and John Clarkson, 2005].

Another criticism put forward with regards to robust design is towards the large focus on statistical methods to find robust solutions. Smith and Clarkson [Smith and John Clarkson, 2005] made a distinction between reliability methods and robustness methods. They use a definition of reliability from British Standard BS 4778-3.1:1991 cited as reliability is ”the probability that an item can perform a required function under given conditions for a given time interval”. Furthermore, robustness is ”functional insensitivity to the effects of stochastic variation”. Robustness methods in this instance are methods that improve reliability through improved robustness, whereas reliability methods are those that improve reliability though some other means. According to these authors, robust design is a design that breaks the dependence between contextual variety (environmental noise) and formal variety (the geometry of parts) and between formal variety and functional variety, see Figure 2.6.

Arvidsson and Gremyr [Arvidsson and Gremyr, 2008] state that ”Robust design methodology means a systematic effort to achieve insensitivity to noise factors. These efforts are based on an awareness of variation and are applicable to all stages of product design.” This definition reveals a more holistic view than the statistical methods of Taguchi. It is, however, not that instructive. In an article by Hasenkamp et al. [Hasenkamp et al., 2009] the authors characterize robust design methodology into principles, practices, and tools, see Figure 2.7. They propose a model aimed at encouraging the engineers to find solutions to the problems rather than a dogmatic use of common tools.

To summarize, one critique of robust design methodology from both the statistics- and engineering community is that the tools in robust design may be useful, but they should not be used without analyzing the given problem to find the best strategy to improve the situation.

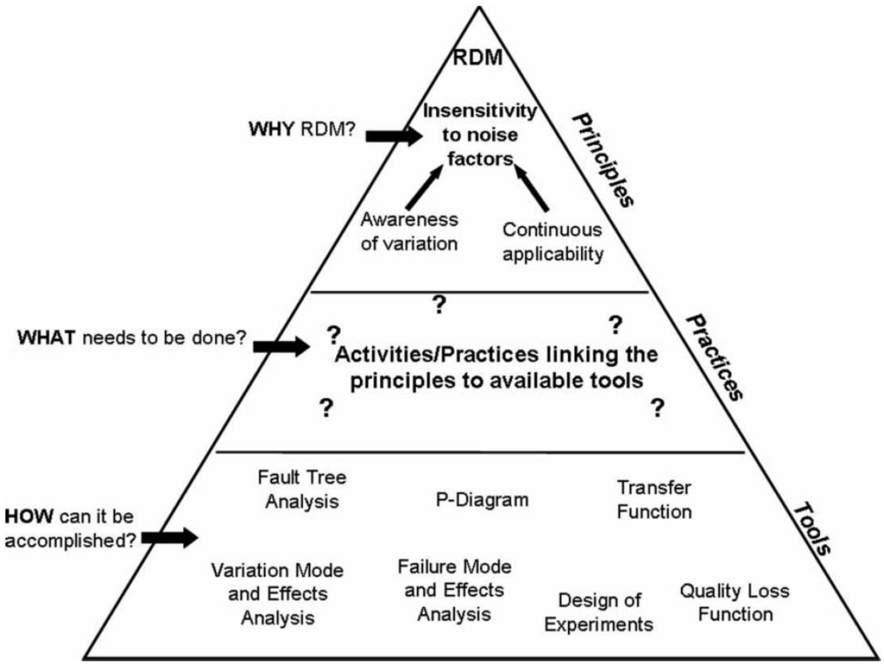


Figure 2.7: Principles, practices, and tools of the robust design methodology [Hasenkamp et al., 2009].

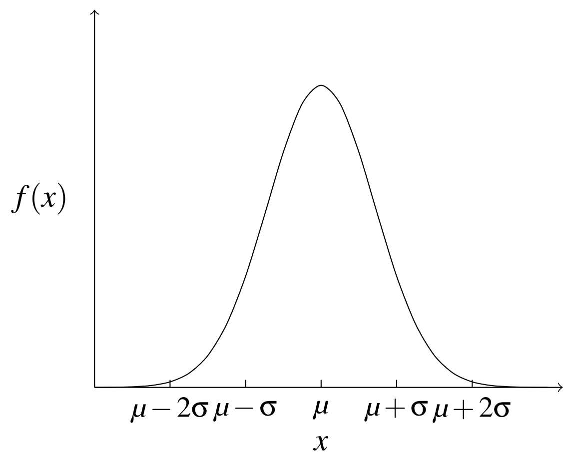


Figure 2.8: The probability density function of a normal distribution.

2.4 Basic statistics and probability analysis

In statistical analysis the concern is to make inference on data sets. Assuming a continuous stochastic variable, X, the density function, $f(x)$, states the probability density of the stochastic variable at x. The most common statistical distribution in connection with industrial application is the *normal distribution*. The central limit theorem in probability theory states that under pretty general assumption, if a stochastic variable is defined as a mean of other stochastic variables, the result has asymptotically a normal distribution, see [Fischer, 2010] for the historical development of the central limit theorem under different assumptions. Hence, if no additional information is given, the assumption of normal distribution of quantities in an industrial setting is often sound, see for example [Chase and Parkinson, 1991].

The normal distribution is characterized by two parameters: its mean, μ, and its variation σ^2. The mean value denots the center of the distribution and the variation is a measure of the spread of the distribution. The density function of a normal distribution is defined by

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \tag{2.2}$$

and is plotted in Figure 2.8. Some commonly used statistical entities are summarized in Table 2.1 inspired by [Wärmefjord, 2011].

Table 2.1: Some common statistical enteties in tolerance analysis.

Notation	Formual	Comment
Probability density function	$f(x)$	a continous function with property $\int_{-\infty}^{\infty} f(x)dx = 1$.
Mean value	$\mu = E[X] = \int_{-\infty}^{\infty} xf(x)dx$	Mean value of population.
Variance	$\sigma^2 = E[(\mu - X)^2]$	
Standard deviation	$\sigma = \sqrt{\sigma^2}$	
Sample mean	$\bar{x} = \frac{1}{N}\sum_1^N x_i$	
Sample variance	$s^2 = \frac{1}{N-1}\sum_1^N (x_i - \bar{x})^2$	Unbiased approximation of variance from a sample.
Capability index	$C_p = \frac{USL-LSL}{6\sigma}$	see Section 2.5.1.
Adjusted capability index	$C_{pk} = \min\{\lvert\frac{USL-\mu}{3\sigma}\rvert, \lvert\frac{LSL-\mu}{3\sigma}\rvert\}$	see Section 2.5.1
Distribution function	$P(a < x < b) = F(a) - F(b) = \int_a^b f(x)dx$	Therefore, $f(z) = \frac{d}{dx}F(x)\mid_{x=z}$.

2.5 Geometry assurance and tolerance management

Variation of parts and processes should, preferably, be considered during the design phase when the concepts are being developed. Here, the cost associated with a design change is low and it is possible to compare different concepts and to optimize design parameters in order to increase the quality of the product.

Part variation comes from variation in the manufacturing process and wear in manufacturing tools. This variation, together with variation in fixtures and variation in the assembly process, lead to geometric variation of the final product. The major contributors to variation are shown in Figure 2.9. How variation will propagate and accumulate, further, is dependent on the robustness of the design solution [Söderberg et al., 2006].

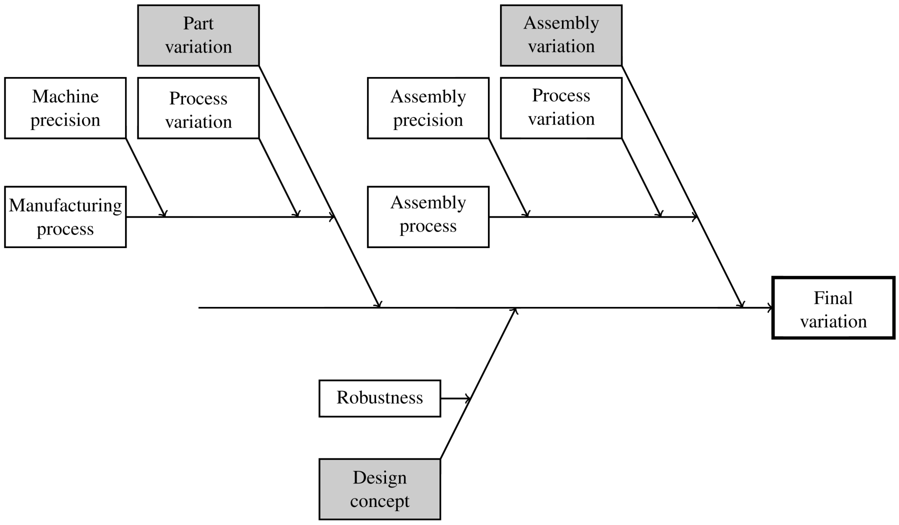


Figure 2.9: Contributors to final geometric variation [Söderberg et al., 2006].

2.5.1 Tolerances

Which tolerances to apply is a further important factor affecting the final variation of products. There has been a substantial amount of research on tolerancing, see for example [Hong and Chang, 2002] and [Shah et al., 2007] for an overview.

There are two types of tolerancing schemes; the traditional dimensional tolerances where limits are set on the dimensions of parts and products, and geometric dimensioning and tolerances (GD&T) where limits are set on form, orientation, location, run-out, profile and symmetry, see [Shah et al., 2007].

Tolerances can be applied using a top-down or a bottom up approach. In the top down approach, requirements are set on the function of the assembled product. These requirements are broken down from tolerances on subsystems down to tolerances on individual parts. This approach has been treated in [Söderberg, 1993, Söderberg, 1994a,Söderberg, 1994b,Söderberg, 1995,Lööf, 2010] and [Wärmefjord, 2011]. In the bottom-up strategy, on the other hand, tolerances are based on experiences of similar parts or some generic tolerances are applied. In both strategies it is important to be able to predict the accumulation of tolerances from parts and fixtures to realized products. In the top-down approach it is necessary to assure that the broken-down tolerances do in fact lead to the requirements set; in the bottom-up approach the designer needs to assure that the realized product is likely to fulfill its purpose. In theory, the bottom-up approach is preferable where the requirements serve as the starting point. There are, however, situations where it is difficult to affect what tolerances are feasible. In practice, a combination of the two approaches is often used.

One strategy to increase the number of realized units within its requirements would be to put tight tolerances on parts and fixtures. However, since tight tolerances are associated with high cost, there are competing requirements between cost and tight tolerances. Products whose functionality hinges on tight tolerances should therefore be avoided and geometrically robust solution strived for [Söderberg et al., 2006]. Before turning to methods for making geometrically robust solutions, the concept of locating schemes will be introduced along with an introduction to variation analysis.

2.5.2 Locating schemes

Locating schemes are central to geometry assurance. The concept of locating schemes was introduced in the previous chapter, but will be elaborated in more detail here.

A locating scheme is a definition of how a part is positioned in a fixture, or to mating parts in an assembly. A rigid body has 6 degrees of freedom in space, 3-translational and 3-rotational. Therefore, in this context 6 points on the object together with the normal direction of the surface at these points, are used to define its position in space. It is, however, possible to approximate 1 point to associated several normal directions, as long as all three translation and three rotation degrees are properly defined. An example of this is a positioning scheme that is physically realized with pins, slots and holes. In Figure 2.11, an example with three pins that determines the A-plane, and one hole and one slot that determine the B- and the C-planes. The hole locates the part in two dimension, and with reference to Figure 2.11, the center of the hole is both one of the B-point and the C-point. Finally, the center of the slot is the position of the final B-point. To be able to manage variation, it is important to have clearly defined positioning points, in contrast to a design where the parts' positions are determined on where the contact between adjacent parts just happened to occur.

One of the most common positioning systems for rigid assemblies is the so called $3-2-1$ positioning system. Here it is easy to get an overview of how the translations and rotations are controlled. One example of a $3-2-1$ positioning system can be seen in Figure 2.10. Here, 3-points, called A-points in the picture, are used to lock the geometry in the z-direction. Together these points define a plane which determines the translation in the z-direction and rotation around the x- and y-axis. The two B-points are used to lock the geometry in a direction orthogonal to the direction that locks the A-points. In this figure the ”B”-points determine the position of the part in the y-direction and rotation around the z-direction. A final point, C, determines the position in the last degree of freedom, translation in x.

For geometries that have a more irregular shape it is sometimes not possible to use a $3-2-1$ positioning system with orthogonal localization directions. In these situations, it is possible to define a 6-*direction locating scheme*, with 6-different directions (as long as the positioning system is non-singular, meaning that it determines all 6-degrees of freedom). For an overview of positioning systems, see [Söderberg et al., 2006].

A deviation in the normal direction in one of the positioning points will result in a rigid body motion. In variation simulation it is often assumed that these deviations are small in comparison to the overall dimension of the part. Here, it is possible to deduce a linear equation relating displacement in a critical dimension, $d_{critical\ dim}$ to deviation in locating points $\delta_{locating\ point}$ by

$$d_{critical\ dim} = A\delta_{locating\ point} \tag{2.3}$$

where each row in A is defined by

$$a_i^T = \begin{bmatrix} (\mathbf{x}_i \times \mathbf{m}_i)^T & m_i^T \end{bmatrix} J^{-1}, \tag{2.4}$$

$\mathbf{x}_i$ is the coordinate of the critical dimension i, $\mathbf{m}_i$ is the direction of the critical dimension and

$$J = \begin{bmatrix} (Lp_1 \times \mathbf{n}_1)^T & \mathbf{n}_1^T \\ (Lp_2 \times \mathbf{n}_2)^T & \mathbf{n}_2^T \\ \vdots & \vdots \\ (Lp_6 \times \mathbf{n}_6)^T & \mathbf{n}_6^T \end{bmatrix} \tag{2.5}$$

where Lp_i and $\mathbf{n}_i$ are respectively the coordinates of and the normal direction of the part at locator point i. A derivation can be found in [Söderberg and Carlson, 1999].

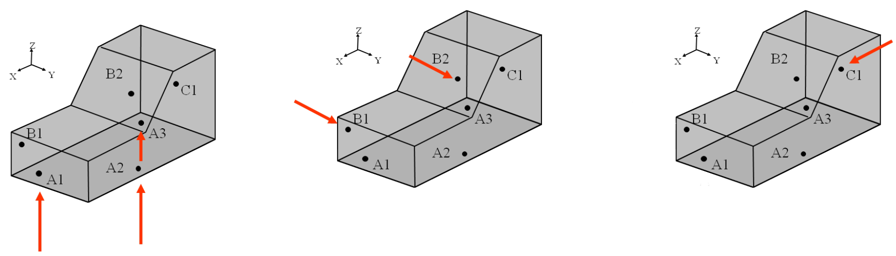


Figure 2.10: A $3-2-1$ positioning system, often used for rigid bodies. To the left, the A-points, in the middle the B-points, and to the right the C-point.

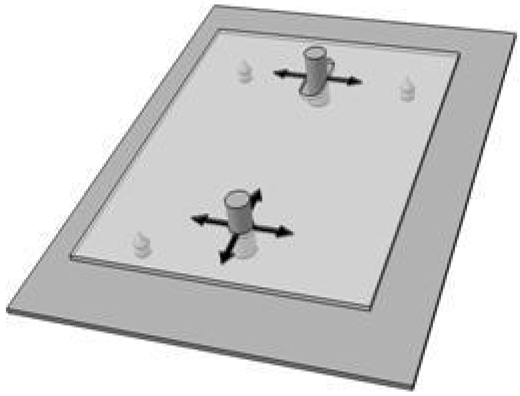


Figure 2.11: Physical realization of a locating scheme using pins, holes and slots. The picture is adjusted from [Wagersten, 2013].

2.5.3 Tolerance analysis

In tolerance analysis the aim is to predict how tolerances propagate and accumulate during assembly operation through to final product. There are many ways to do this. Overview of the research area of tolerance analysis can be found in [Nigam and Turner, 1995, Chase and Parkinson, 1991, Gao et al., 1998, Hong and Chang, 2002] or [Shah et al., 2007].

There are generally two approaches when predicting assembled variation; an analytical approach or the Monte Carlo (MC) approach.

The analytical approach is usually based on some Taylor expansion of the function relating input variation to variation of critical assembly measures,

$$f(X_1, X_2, \dots, X_n) \approx f(\mu_1, \mu_2, \dots, \mu_n) + \sum_{i=1}^{n} \frac{\partial f(\mu_1, \mu_2, \dots, \mu_n)}{\partial x_i} (X_i - \mu_i), \qquad (2.6)$$

where μ denotes the mean of the stochastical variable X_i. In *worst case* tolerance analysis, the accumulated assembly tolerance T is calculated based on all stochastic dimensions being at their worst tolerated value, t_i, at the same time. Setting tolerances according to this approach will lead to products that will comply with requirements. However, the probability that all dimensions will exhibit their extreme values is very low. This will lead to an overly pessimistic tolerance accumulation [Nigam and Turner, 1995]. Another approach is statistical tolerancing. Here, the tolerances are connected to assumed statistical distributions of the critical dimension in question. In Root Sum Square, RSS, the tolerances t_i are identified with $\pm n\sigma$, for some n, where σ denotes standard deviation. Assuming small deviations from nominal values and independence in input variation, the variation of the output measure, T, can be approximated as

$$T = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f(\mu_1, \mu_2, \ldots, \mu_n)}{\partial x_i} t_i \right)^2}, \tag{2.7}$$

[Evans, 1975]. In addition, if the tolerances, T_i, are assumed to be normally distributed, the output distribution is also normally distribution, since a linear combination of normally distributed variables is normally distributed . Often, the distribution of the output measure can also be assumed to be normal under more general assumptions due to the central limit theory. In contrast to worst-case analysis, the RSS-value gives an overly optimistic tolerance prediction [Nigam and Turner, 1995]. The RSS-value is therefore sometimes modified using a scale factor. There are also combinations of these measures and measures to account for mean value drifts. For a compilation of tolerance accumulation models based on Chase and Parkinson [Chase and Parkinson, 1991] and Wu and Tang [Wu and Tang, 1998], see [Lööf, 2010].

Sometimes higher order Taylor expansions are used, see for example [Nigam and Turner, 1995, Cai et al., 2006]. In Cai et al. [Cai et al., 2006], for example, a second order Taylor expansion,

$$\boldsymbol{f}(\boldsymbol{X}) \approx \boldsymbol{f}(\boldsymbol{\mu}) + \sum_{i=1}^{n} \frac{\partial \boldsymbol{f}(\boldsymbol{\mu})}{\partial x_i} (X_i - \mu_i) + \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{\partial \boldsymbol{f}(\boldsymbol{\mu})}{\partial x_i} \frac{\partial \boldsymbol{f}(\boldsymbol{\mu})}{\partial x_j} (X_i - \mu_i) \left(X_j - \mu_j \right), \tag{2.8}$$

is used. The mean and the variation of the critical measures are here obtained by

$$E\left(\boldsymbol{f}(\boldsymbol{X})\right) \approx \boldsymbol{f}(\boldsymbol{\mu}) + \frac{1}{2} \sum_{i=1}^{n} \frac{\partial^2 \boldsymbol{f}(\boldsymbol{\mu})}{\partial x_i} \sigma_i^2 \tag{2.9}$$

and

$$\boldsymbol{\sigma}^2(\boldsymbol{f}(\boldsymbol{X})) \approx \sum_{i=1}^{n} \left(\frac{\partial \boldsymbol{f}(\boldsymbol{\mu})}{\partial x_i} \right)^2 \sigma_i^2 + \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\frac{\partial^2 \boldsymbol{f}(\boldsymbol{\mu})}{\partial x_i} \right)^2 \sigma_i^2 \sigma_j^2, \tag{2.10}$$

again under the assumption of indenpendent input variation. This approach can be computationally very fast. However, this approach has some draw backs that the authors themselves acknowledge; 1) the function f needs to be close to quadratic in order for the second order Taylor expansion to be a good approximation, which is not the case for assemblies with parts in contact (see Section 2.6.2 below), and 2) due to surface continuity tolerances will often have some correlation.

Analytical methods are often computationally cheap. However, it can be difficult to derive analytical expressions and the associated Taylor expansion. Furthermore, as stated above, the accuracy of the deterministic methods have been questioned [Cai et al., 2006].

Another approach is based on MC-Simulation. The method was first used for physics applications for handling complex integrals and differential equations [Metropolis and Ulam, 1949, Metropolis, 1987]. The MC-simulation technique is based on generating a large number of samples from input distributions. This input is used iteratively in the assembly function to derive the distributions of critical measures, see Figure 2.12. MC-Simulations capture both linear and non-linear relationships. It may, however, require a large number of samples to draw correct inferences from the simulation. This is because the MC-simulation converges as $O(n^{-1/2})$. The technique can therefore be computationally demanding and time consuming [Nigam and Turner, 1995].

The Capability index, C_p, is a measure that relates tolerances to the variability of the process. It is defined as $C_p = \frac{USL-LSL}{6\sigma}$, where USL is the upper specification limit and LSL is the lower specification limit. A capability index of 1 indicates that 99.7% of the produced units will be within tolerances. For processes where the upper and lower limits are not symmetric around the nominal value the adjusted capability index C_{pk} is preferred, defined as $C_{pk} = \frac{\min(|\hat{x}-USL|,|\hat{x}-LSL|)}{3\sigma}$, since this is more conservative than C_p.

2.6 Computer aided tolerancing

There are several commercially available tolerance analysis software packages, see [Lööf, 2010] for a compilation. In this project the software package RD&T has been used. RD&T is based on MC-simulation and has Finite Element Analysis (FEA) capability to enable non-rigid variation simulation, see Section 2.6.1.

A typical working order in geometry assurance has been presented in [Söderberg et al., 2006] and its functionality can be seen as addressing two of Phadke's levels of design; parameter design and tolerance design [Phadke, 1995], through stability analysis, respectively variation simulation and contribution analysis.

The first CAT-analysis in geometry assurance is, typically, stability analysis. The aim is to find a locating scheme that is robust, regardless of the tolerances applied. During stability analysis, a unit disturbance is applied to every locating point in the controlling direction, one at a time, and the amplification of this unit disturbance to critical measures can be studied using a root sum square approach. In Figure 2.13, an example of a stability analysis is given, where the amplification of variation is color coded. Stability analysis enables the comparison of different positioning systems and it is possible to optimize the position of the locators early

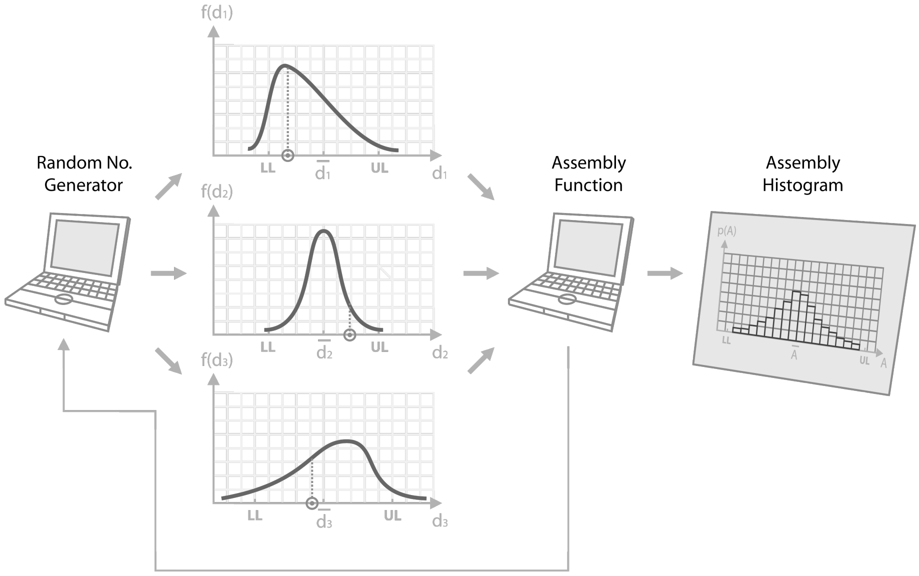


Figure 2.12: A schematic description of the assembly simulation using the Monte Carlo Method. This picture is from [Forslund, 2011] based on a figure appearing in [Chase and Parkinson, 1991].

in the design phase. In, addition stability analysis can be used to decrease the coupledness of the locating schemes.

The next logical step, after stability analysis, is to assign tolerances to the locating point given the information at hand. This information can be standard tolerances based on the dimensions and the manufacturing process of the part, based on experience from similar parts, or variation simulation of the manufacturing process. Given this input, it is possible to simulate the accumulation of variance of the assembly using MC-simulation by applying a set of distributions based on the tolerances, as input disturbances. Graphical tools, such as color-coding and histograms of the simulated distribution of critical measures, along with information of mean values, standard deviation and capability measures, can be presented, see Figure 2.13.

For critical measures that are outside the tolerance limit, there are two alternatives; either decrease tolerances for the mating surfaces in the locating schemes or iterate back and create a more robust positioning system. Since tight tolerances are associated with high cost, as mentioned in Section 2.5.1, it is preferable to decrease the tolerances on as few surfaces as possible. In contribution analysis, it is possible to analyze how much the input variances contribute to a specific critical measure. For critical measures outside the tolerance limit, it is possible to tighten the tolerance only on the surfaces that contribute the most to the variance of the

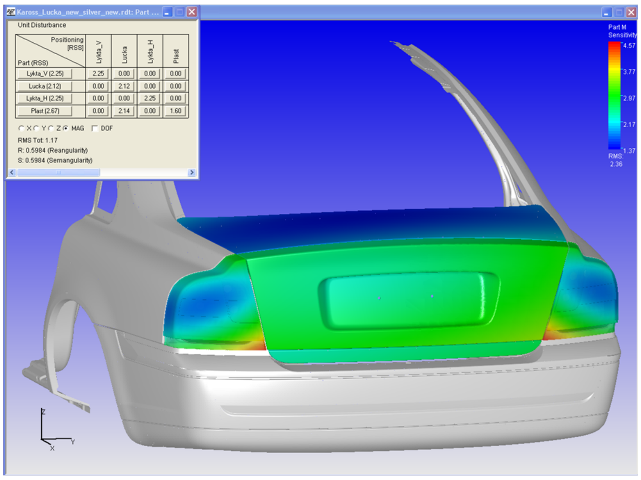


Figure 2.13: The result of a stability analysis. The amplification of variation is color coded as RSS-values. To the left; a stability matric denoting the coupledness of the positioning system.

critical measure. There are, also, methods to automatically allocate tolerances, see [Lööf, 2010] for an overview.

2.6.1 Non-rigid variation simulation

In rigid variation simulation the parts are assumed to be rigid. For sheet metal, or plastic components, to mention two examples, these assumption may not be a good approximation of the assembly situation. For non-rigid assemblies the parts can be over-constrained, i.e. forced in place by fixating more than 6 degrees of freedom. This can be realized using clamps, welding points, fasteners etc., to compensate for gravitational effects, parts variation or fixturing errors. In these situations, Cai et al [Cai et al., 1996] proposed the $N-2-1$ locating scheme to restrain motion out of surface.

One example of positioning systems for compliant parts can be seen in Figure 2.15. The master locating system, MLS, is the subsystem of the locating scheme that determines the position of the parts. In Figure 2.15, the MLS is marked with filled flags, while the additional support points are marked with empty flags.

For a positioning system that locks more than 6 degrees of freedom, deviation in the contact surface of the MLS will result in a rigid body transformation. When additional locators are brought into contact, the parts will deform. The deformation can be simulated using FEM, see Section 2.7 below.

In the Direct MC-Method, the full FEM-problem is solved iteratively, with

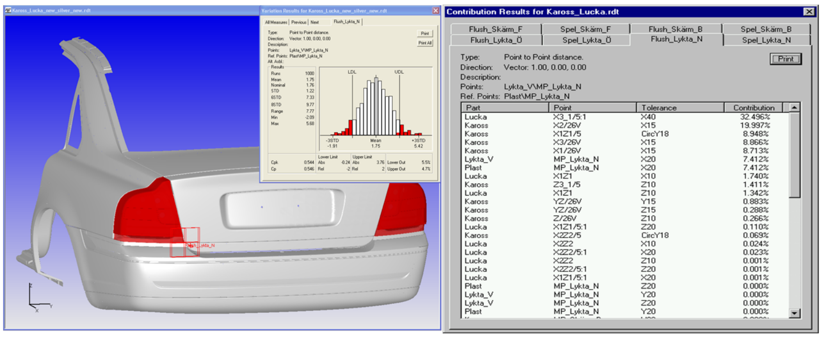


Figure 2.14: To the left; the result of a MC-simulation for a specific critical measure. To the right; the contributing factors to variation in the critical measures are displayed in order of magnitude.

variations in the boundary conditions. This method is accurate, can capture non-linear effects and is not restricted to specific distributions. The drawback is that it can be very time consuming, which can be a difficulty especially for industrial applications.

The Method of Influence Coefficient (MIC) is a method that was proposed by Liu and Hu to be able to perform compliant variation simulation more efficiently [Liu and Hu, 1997]. In the MIC, a linear relation is established by applying a unit disturbance for all points, again one at a time, that are in contact with adjacent parts or fixtures except the MLS, in the direction of contact. These points include "support points" i.e. additional locators, fasteners, and clamps and weld points. Also, to include contact modeling a unit force is applied for all contact pairs (see 2.6.2). The deformation response to this unit disturbance is evaluated using FEM, and recorded in a vector, s_i.

For assemblies including spot welding, there are two alternative procedure. One is using a *position gun* and the other is using a *balanced gun*. To determine the final shape of the assembly using a position gun;

1. the parts are initially put in an assembly fixture. Here, part and assembly fixture deviations lead to position errors, $u_{position\ error}$, that is; a rigid body motion for all parts in the assembly calculated using Equation (2.3), using all nodes as a critical dimension. From the non-nominal position, and deviation in support and and weld points, the distance, δ, for these points to their mating points in the surrounding assembly is calculated. Now, the deformation of the parts in the assembly is calculated by

$$u_{deformation} = S\delta, \tag{2.11}$$

where S is the matrix with responses, s_i, corresponding to support and weld points as columns.

2. The displacement of the points are now determined by $u = u_{part} + u_{position\ error} + u_{deformation}$.
   (a) In addition, some of the parts may penetrate other parts resulting in an additional deformation contribution that comes from contact forces (see Section 2.6.2), hence, $u = u_{part} + u_{position} + u_{deformation} + u_{contact}$.
3. The weld points are fixated using a stiff beam. This is mathematically realized by adding penalty terms in a joint stiffness matrix that forces the two weld nodes to be fixed in relation to one another. Therefore, new sensitivity responses need to be calculated for the spot welded assembly.
4. Now, the clamps are released causing spring back and the assembly is put in a measurement fixture. The spring back is calculated by applying a force equal in size to the clamp force, but in the opposite direction.
5. The final displacement in the measurement fixture is calculated in a similar way as in the assembly fixture described in points 1 and 2.

If instead a balancing gun is used, two forces, equal in size and pointing in opposite direction, are applied to the two weld points so that they are brought into contact and then a stiff beam is used to fixate the two weld points.

For many of the appended papers, there are no weldpoints[1]. In this case the assembly fixture is the measurement fixture and only one calculation per iteration is required.

2.6.2 Contact modeling

As described in the previous section, when performing compliant variation simulation it is possible for the parts to penetrate other parts in the assembly. To avoid this rather nonphysical behavior, contact modeling is used in connection with compliant variation simulation [Cai et al., 2006, Dahlström and Lindkvist, 2007, Wärmefjord et al., 2008, Ungemach and Mantwill, 2009]. If two parts are in contact they will impose a force to prevent penetration. In contrast, if there is no penetration there will be no force. Therefore, contact modeling is a non-linear phenomenon. In contact modeling, contact pairs, consisting of a master and a slave, node are defined. Together with every master node, a plane is defined. If

[1]It is worth noting that weld points are used for every joining operation that fixates two points in its clamped position. This is in contrast to, for example, a pin and a pin hole.

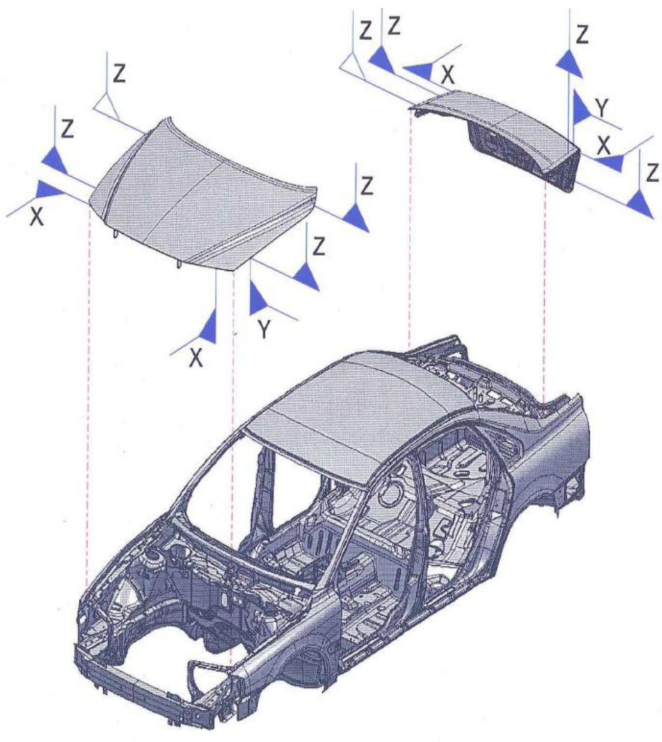


Figure 2.15: An example of two $4-2-1$ locating schemes for compliant parts.

the distance, d_i, between the master node and the slave node, along the normal to this plane, is negative, a penetration is detected. The problem is to find the set of reaction forces, R_i, acting on both the master and the slave node so that for all contact pairs the relation $d_i \geq 0$ holds and, conversely, if $d_i > 0$ then $R_i = 0$.

Algorithms describing contact modeling within variation simulation can be found in [Cai et al., 2006,Dahlström and Lindkvist, 2007,Wärmefjord et al., 2008] and [Ungemach and Mantwill, 2009]. These algorithms are based on a heuristic method of iteratively applying adjustments to the contact forces until the contact condition is fulfilled.

In the more general FEM context a number of methods have been developed for contact modeling [Wriggers and Laursen, 2006]. A general approach for solving contact problem in FEM as a quadratic programming problem is presented in [Conry and Seireg, 1971]. This general approach is used to formulate a quadratic programming problem for variation simulation using MIC in Paper G.

2.7 Introduction to the finite element method

The Finite Element Method (FEM) is used extensively in this work. It is a method to calculate approximations of boundary value problems. In this work it is used to calculate the displacements and stresses in non-rigid variation simulation (section 2.6.1 above) and to calculate the heat flow and distortion in welding. The basic idea in the finite element method is that the geometry of interest is approximated by a number of small standard elements, see Figure 2.16. Inside each element the fields (temperature, displacements etc.) are approximated by functions that are a superpositions of base functions $\psi(\boldsymbol{x})$, with the value of the fields at specific points of the element called nodes (the black dots in Figure 2.16), as weights. The exterior nodes of the element are, furthermore, generally shared by other elements so that the (primal) field variables are continuous across element boundaries. Using the shape functions a local boundary condition problem is formulated, for every element, of finding the closest approximation of the field variables at the nodes, given the shape functions and the size of the element. By imposing equilibrium between the element boundaries it is possible to build an algebraic system to solve for the field variables in each node globally, given appropriate global boundary conditions.

Details describing the finite element method can be found in standard introductions to the subject such as [Zienkiewicz and R. L. Taylor, 2005] and [Johnson, 2012].

2.8 Introduction to polymers

In this section a brief introduction to polymers is given. ”Plastics” is a term used to denote the technical usage of *polymers*, often with additives such as stabilizers. Polymers are materials composed of long, often organic polymer chains. Polymers can be classified as *crystalline*- or *amorphous*. In crystalline polymers the majority of the polymers are ordered in a symmetric pattern in space. Polymers that do not have this structure are called amorphous. Crystalline polymers have high fatigue strength which makes them common in, for example, cogwheels or snaps, while the creep resistant property of amorphous plastics makes them common in products such as exterior car parts. Furthermore, the polymer chain can be linear, linked or have a network structure. Plastics composed of polymers that are linear or linked are called thermoplastics while plastics with a network structure are called thermosetting plastics.

Many polymers exhibit mechanical properties that very highly with temperature. In this work, the geometry is of interest and, therefore, the structural characteristics of the polymers. In comparison to metals, the coefficient of thermal

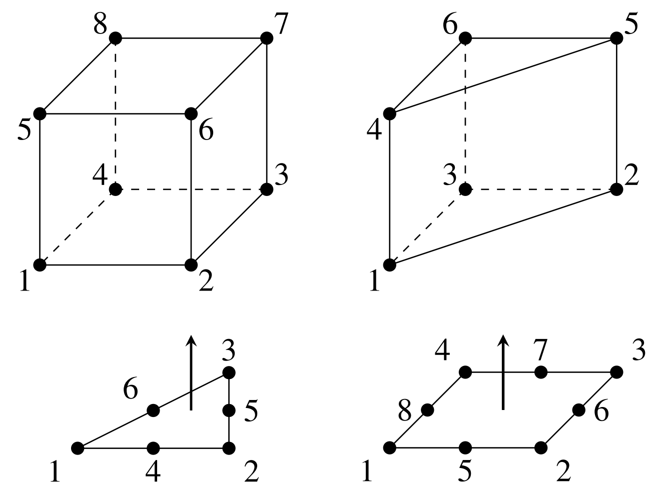


Figure 2.16: Examples of four standard finite elements that are used to approximate the geometry of interest in a finite element simulation. The black dots are the nodes that are numbered by their internal numbering convention.

expansion can be significantly higher for polymers. Furthermore, the coefficient of thermal coefficient is often increasing with temperature, but a tabulated value is usually taken as a mean value over the functional temperature span, see for example the standard ASTM D696 [AST, 2014].

The stress-strain relationship may include a tensile modulus that for certain temperature ranges varies drastically. For instance, linear amorphous polymers have glassy-transition-rubbery flow regions where the Young's modulus is nearly constant in the glassy and rubbery plateau, but decrease rapidly with temperature in the transition and flow regions. For a crystalline polymer the Young's modulus decreases gradually with temperature up to a melting point, see Figure 2.17. These behaviors have been summarized by Aklonis [Aklonis, 1981].

The yield point is a point in stress space at which irrecoverable deformation occurs. For polymers the distinction between recoverable and irrecoverable are not as distinct as for metals. Furthermore, for polymers the ductility can vary widely, where some fracture before the yielding point and other can be stretched far after the yielding points [McCrum et al., 1997]. When predicting yielding in polymers the yield criterion used in metals, such as Tresca or von Mises, are often used, however usually with the addition that the yielding point varies with the hydrostatic pressure, the temperature and the strain rate [McCrum et al., 1997].

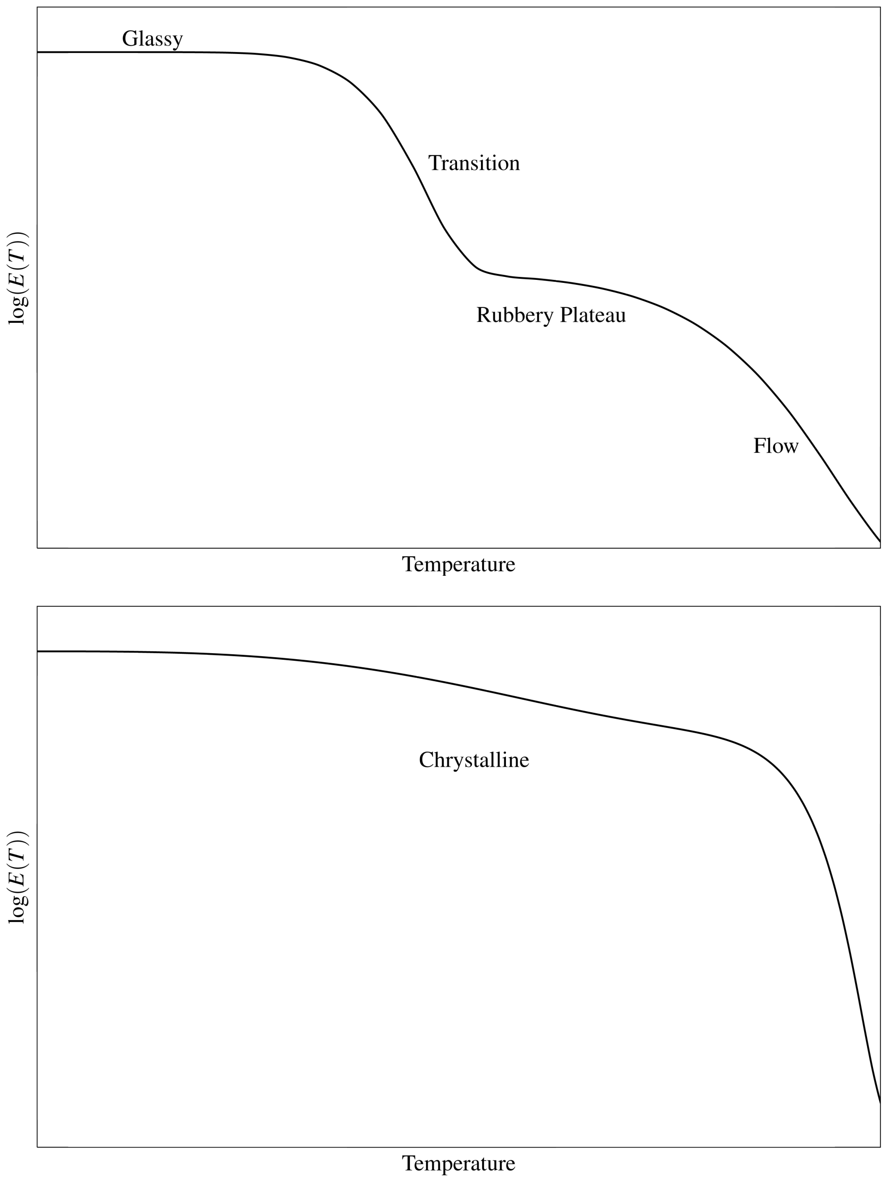


Figure 2.17: A schematic picture of the relation between temperature and Young's modulus. Above an amorphous polymer and below a crystalline [Aklonis, 1981].

2.9 Optimization

Optimization is not central to the work in this theses. However, in Paper G and H optimization is used. Therefore, a short introduction to optimization will be given here.

A general optimization problem can be stated

$$\begin{aligned} \underset{x}{\text{minimize}} \quad & f(x) \\ \text{subject to} \quad & x \in S \end{aligned} \tag{2.12}$$

where, $f(x)$ is an objective function, and x are decision variables constrained to belong to a set $S \subseteq X$. In this thesis, the set S consists of linear equalities and inequalities. Hence, S can be defined as

$$S = \{x \in X| \quad I(x) = \mathbf{0} \quad \& \quad \mathcal{E}(x) \leq \mathbf{0}\} \tag{2.13}$$

for some linear equations I and $\mathcal{E}$. Furthermore, the optimization problems that are formulated in Paper G and H have quadratic objective functions. Optimization problems with a quadratic objective function and a feasible set S consisting of linear functions are known as quadratic programming problems. For these problems efficient algorithms exists.

2.10 Introduction to welding simulation

During assembly, welding is a common joining technique in many industries. Prior to welding the parts that are going to be welded are, typically, placed in fixtures, clamping may sometimes be used to force the structures in place as well as possibly spot-welding. During welding a weld gun is moving through a weld path inducing high temperatures and possibly adding filler material. The material surrounding the weld gun will melt and blend, and when the weld gun has passed, it will cool down and solidify. When the structures cool down, residual stresses and deformation result due to uneven heating and melting.

The modeling of the welding consists in three parts and their coupling; Heat transfer, microstructure evolution and mechanical structure evolution. These all affect each other but the main interactions are from temperature to mechanical structure evolution and microstructure evolution and from microstructure evolution to mechanical structure, see Figure 2.18 [Goldak and Mehdi, 2005]. The other interactions are of minor importance and can often be neglected and are omitted in this work. In addition, the primary interest of this work is on the residual distortion caused by welding. In these causes it has been shown that the effect from

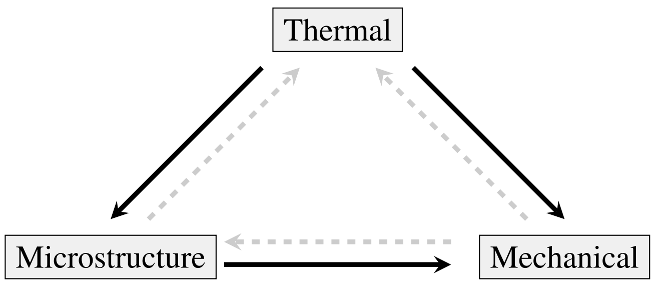


Figure 2.18: The coupling between thermal, mechanical and microstructure in welding analysis. The filled lines express the major influences while the dashed line implies minor influences. Inspired by [Goldak and Mehdi, 2005].

microstructure evolution play a secondary role [Lindgren, 2002]. Therefore, we have not included simulation of microstructure.

Welding simulations are performed using the finite element methods, with temperature dependent material properties. Overviews of computational welding mechanics can, for example be found in [Lindgren, 2001a,Lindgren, 2001b,Lindgren, 2001b,Goldak and Mehdi, 2005] and [Lindgren, 2006].

2.10.1 Heat modeling

It is common practice in welding simulation not to model the physics of the weld gun. Instead a heuristic approach is adopted. This is usually done by defining a heat source that moves along the weld path. Within this heat source a distribution of heat flux is defined.

The two heat source models used in this work are Goldak's double ellipsoid and a conical heat source used to model the heat source during laser welding. Let t denote the time and, assuming that the weld gun is travelling in the z-direction, let (x,y,ξ) denote a local coordinate system. Then, the heat flux for Goldak's double ellipsoid is defined by

$$q(x,y,\xi(t)) = \frac{6\sqrt{3}f_iQ}{abc\pi\sqrt{\pi}}e^{-3x^2/b^2}e^{-3y^2/c^2}e^{-3\xi^2/a_i^2}, \quad i = 1,2, \tag{2.14}$$

and,

$$\xi(t)) = z + \nu(\tau - t), \tag{2.15}$$

where

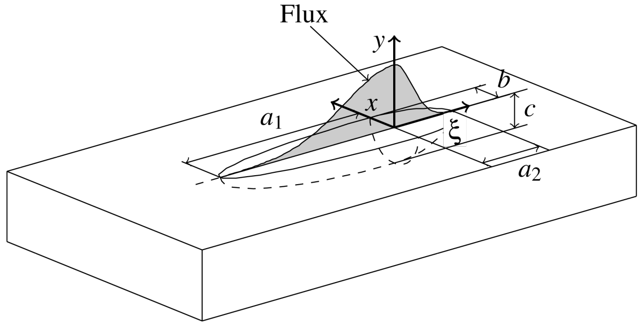


Figure 2.19: Double ellipsoid heat flux [Goldak and Mehdi, 2005].

Q	*is the heat input.*
f_i	*is a weight factor equal to* f_1 *if* $\xi < 0$ *and equal to* f_2 *if* $\xi \geq 0$. *In addition,* $f_1 + f_2 = 2$, *to ensure continuity.*
a_i, b, c	*are constants related to the length, width, and depth of the melting zone.*
ν	*is the speed of the weld gun, and*
τ	*is constant to adjust for the position at* $t = 0$.

Goldak's double ellipsoid is depicted in Figure 2.19.

The heat distribution associated with the conical heat source is defined by

$$q(x, y, \xi(t)) = \frac{2Q}{\pi r_0^2 H} e^{1-3(r/r_0)^2} \left(1 - \frac{-y}{H}\right), \tag{2.16}$$

and

$$r = \left(\xi(t)^2 + x^2\right)^{1/2}, \tag{2.17}$$

where

r_0	*is the radius of the heat input at the surface,*
r	*is the distance from the central axis, and*
y	*is the distance to the surface,*

see Figure 2.20.

If the addition of filler material is simulated, the elements in front of the weld gun (the elements belonging to filler material that have not yet been added) have a large heat transfer coefficient.

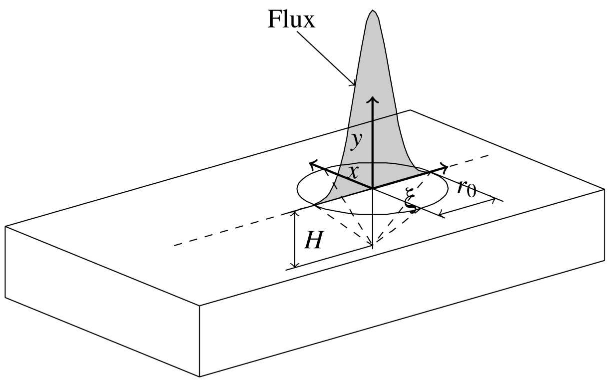


Figure 2.20: The conical heat source.

2.10.2 Mechanical modeling

The coupling between heat transfer and structural mechanics is assumed to be a one-way coupling, as described above. Hence, the structural evolution is a one-way response to the induced heat. An infinitesimal elasto-plastic formulation is used for the structural analysis. Finite strain simulation has been use to validate the assumption of the infinitesimal approximation. These simulation have, however, not been published.

The addition of filler material is simulated by inactivating the part of the mesh corresponding to the filler. When the weld gun passes, the filler material is activated thermally, and when the temperature goes below the solidification temperature, the elements are mechanically activated stress free.

In order to achieve accurate results, the mesh needs to be rather fine around the the weld path in order to resolve the high temperature gradients. Furthermore, the time steps during simulation need to be adjusted against the mesh sizes along the weld path and to the velocity of the weld gun. Because of this, weld simulations can be computationally expansive and simulations of several hours are not uncommon.

2.10.3 Welding distortion simulation based on applied strain

Because of long simulation times, methods have been proposed to estimate weld induced deformation that are faster than the full transient elasto-plastic simulation, described in 2.10.1 and 2.10.2. These methods are usually based on the assumption that the driving force in weld induced deformation is shrinkage of the material that melts, and then cools down and regains its mechanical stiffness. In these methods, an applied strain is imposed on the structure. However, there have been different suggestions as to what strain should be applied and to what region.

One strategy called *Inherent strain* was proposed by Ueda et al. [Ueda et al., 1989, Ueda and Yuan, 1989, Ueda and Yuan, 1993]. Inherent strain was initially used for stress analysis but later also for distortion prediction, see for example [Murakawa et al., 1996, Liang et al., 2005, Deng and Murakawa, 2008]. As input to this method, either a transient simulation to model welding of a small segment of the the joint or experimental results are used. An inverse formula is then used to obtain what is called the inherent strain. These strains are assumed to cause the residual weld induced distortion or stress. To obtain the distortion of the complete structure, the inherent strains are applied around the weld joint as initial strains and the final shape is calculated using an elastic material model.

Another approach is proposed by Camilleri et al. and Mollicone et al. [Camilleri et al., 2005, Camilleri and Gray, 2005, Camilleri et al., 2006, Mollicone et al., 2006]. Here the deformations are divided into distortion stemming from longitudinal contraction and transverse welding deformation. The longitudinal contraction is modelled by prescribing a thermal strain to different volumes (or areas depending on if the simulation is 2- or 3 dimensional). These volumes are categorized according to its maximum temperature during welding, which is calculated using an analytic expression. The transverse deformation is similarly expressed using analytical formulas based on the assumption that transverse deformation stems from the contraction of the melted zone [Camilleri et al., 2005].

Yet another approach is the volumetric shrinkage method. Here, the welding distortion is more directly related to the thermal contraction when the melted material is cooled down to the ambient temperature. This approach has been shown to give reasonable results, see for example [Bachorski et al., 1999] and [Sulaiman et al., 2011].

2.10.4 Tolerance simulation in combination with welding simulation

There has not been much previous work focused on welding simulation aimed at geometric variation and tolerance analysis[2]. Lee et al. used the approach of a predefined database to include variation of process parameters such as welding speed, maximum temperature, cooling speed, material properties, and thickness of the parts that are joined into variation simulation [Lee et al., 2009b]. Another approach was proposed by Xiong et al. [Xiong et al., 2002]. Here a statistical

[2]spot welding is an exception, see [Wärmefjord, 2011] and [Segeborn, 2011] for two overviews of using spot welding in variation simulation. However, the effect of heat is not usually taken into account.

error analysis model is proposed that includes manufacturing error, fixture error, and process error, such as welding error, in a multi-station assembly setting. Here welding error is included as an input to the analysis.

In both [Lee et al., 2009b] and [Xiong et al., 2002] the welding deformation is considered independent of geometric errors. However, in a study performed in 2010, it was shown that welding distortion is dependent on displacements of the parts prior to welding [Pahkamaa et al., 2012]. This means that for accurate prediction of the outcome of a welded assembly, variation simulation and welding simulation need to be considered simultaneously. However, the large simulation times together with the large number of MC-runs that are needed for statistical inference in variation simulation make the combination of transient variation simulation with variation simulation unfeasible for the industrial context.

2.11 Quality of simulation

One important aspect to consider when doing research involving development of computer aided design tools is the quality of simulation. According to Bracewell [Bracewell et al., 2001] there are generally two ways to do this; 1) theoretical validation i.e. comparison to a known benchmark problem and 2) experimental validation. Here, a discussion will be given of the quality of MIC-, contact modeling and welding simulation. Also, a discussion of the influencing factors for the assembly outcome and what has been considered is included.

The MIC has been validated theoretically by Liu and Hu [Liu and Hu, 1997]. Here, the authors compared MIC with direct MC-techniques using an assembly consisting of two sheet metal parts joined in a slip joint. The authors conclude that the difference between direct MC and the MIC is small. In Liu and Hu [Liu and Hu, 1998] the MIC is compared to experimental measurements on 16 assemblies. The correlation between simulation and experimental data is $R = 0.92$.

Dahlström and Lindkvist [Dahlström and Lindkvist, 2007] compared 1) direct-MC with MIC without contact modeling, 2) direct-MC with and without contact modeling, and 3) direct-MC with MIC with contact modeling. The first comparison revealed that without contact modeling direct-MC and MIC is almost identical. However, there is a significant difference between direct-MC with and without contact modeling. Contact modeling by direct-MC and MIC shows, according to the authors, good agreement. In [Wärmefjord et al., 2008] part variation and variation from the assembly process in contact modeling are compared to inspection data. Correlation between 6 standard deviations from simulation and inspection is $R = 0.83$. Correlation between scanned and simulated results in position error is $R = 0.87$, which can be considered good.

Welding simulations are computationally intensive. In [Lindgren, 2006] Lindgren proposes different accuracy levels depending on the scope of analysis. These are; *reduced accuracy* for early design stage, *basic simulation*, where questions of residual stresses and deformations are of interest for rigid structures[3], *standard simulation* for residual state of the weldment for flexible structure and when the transient phenomena during welding is of interest, *accurate simulation* for simulating the microstructure close to the weld and heat zone, and finally *very accurate simulation* for questions including hot cracking. In this thesis, only residual deformation is of interest. For the transient weld simulation used in this work, the accuracy level can be approximated as standard simulation while the SCV-method (proposed in Paper D and used also in Paper F and G) is, according to this accuracy level definition reduced accuracy, to be used for early design stages and requires simulation of higher accuracy level later in design stages.

As been stated above, in order to assure product quality virtually, it is important to include all the factors contributing to the overall quality. A list of factors that could contribute to assembly variation is inspired by Wärmefjord [Wärmefjord, 2011] is shown in Figure 2.21. That some of these factors influence the geometric variation, such as, material model or number of statistical samples on which to draw inferences are self-evident. In addition, Spensieri, [Spensieri et al., 2009] showed that assembly sequence affects geometric variation. The product environment is treated in Papers B, C and I. Wärmefjord considered fixture repeatability in [Wärmefjord et al., 2010]. Xie and Hsei showed that clamping and joining sequences have an effect on the geometric outcome [Xie and Hsieh, 2002]. Variation in the efficiency of the welding gun and weld speed was illustrated virtually by Lee et al. [Lee et al., 2009a]. Here, dimensional variation was observed. However, the spread of the two parameters is larger than is expected as process variation, which the authors acknowledge.

[3]As a guideline Lindgren considers multipass welds as rigid and other welds as flexible. For flexible structures the the next accuracy level is needed [Lindgren, 2006].

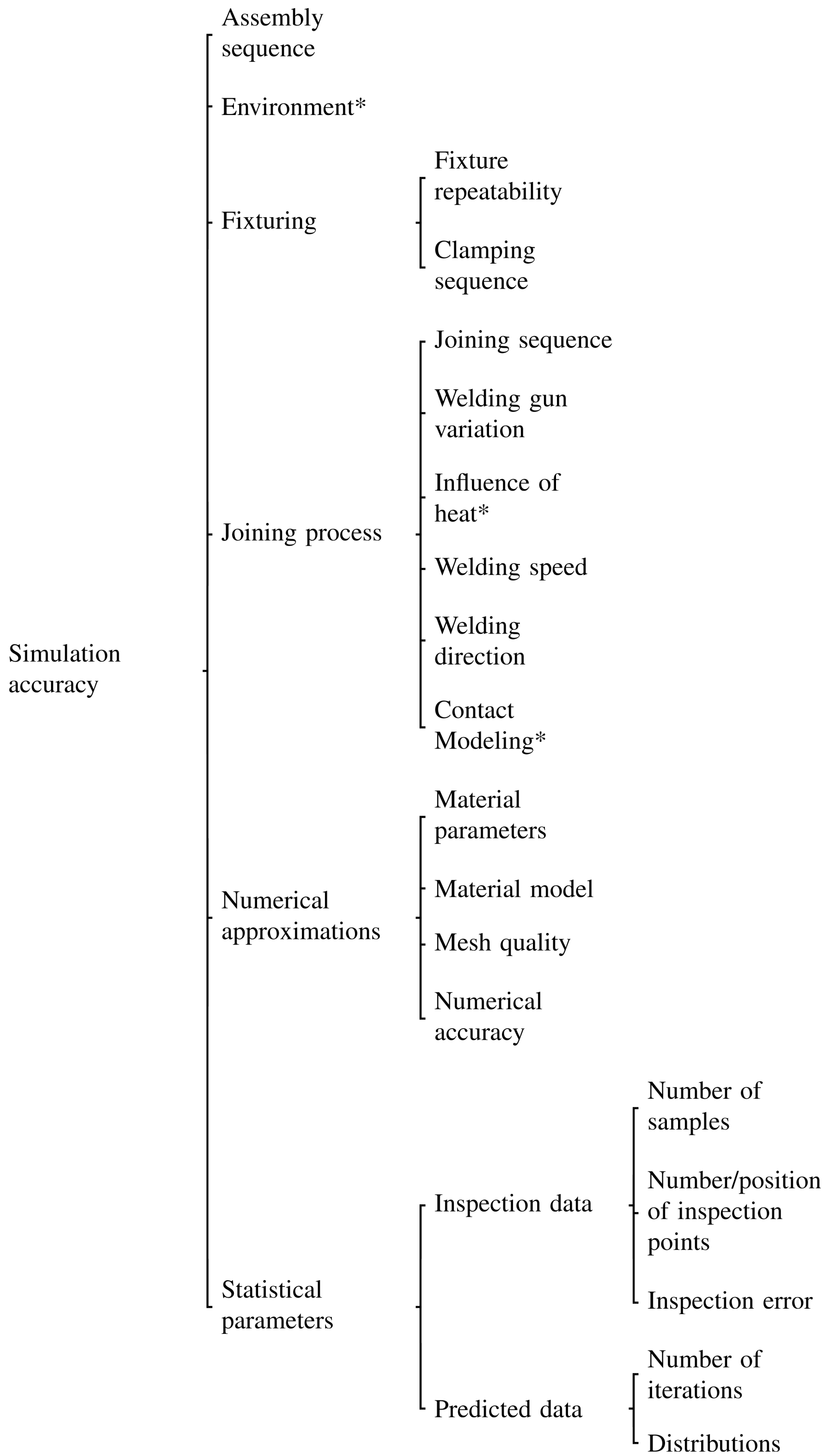


Figure 2.21: Factors that could contribute to variation and that should be considered in variation simulation. Factors with an $*$ are treated in appended papers.

CHAPTER 3

Research Approach

In this chapter a description and justification of the research approach will be given. The research presented in this thesis is within geometry assurance, which can be positioned as a subarea of design science. Therefore, a description of design science and views on research within this field is provided. based on this background, different methodologies will be reviewed in order to describe and justify the methodological approach taken given the research focus of this project. However, every research project is unique, and following a strict prescription on how research shall be done often leads to results that are not optimal [Blessing and Chakrabarti, 2009]. Instead, in every research project the researcher need to reflect on the structures and methods, and the relation between methods that best can aid in the research project in order to justify the research results. In this context results mean the hypothesis created, research questions, the answers to the research questions and their justification.

The background of the researcher will also influence the results of the research. In this project, many of the appended papers are close to applied mathematics. Therefore, another aim in this chapter is to position this research in the context of design science.

3.1 Research in design science

At some level partition in any kind of research is partition in a critical discussion within a research community with a similar view on identified problems and solutions to problems [Kuhn, 1970]. Within design, this discussion is characterized by how to understand design and developing and evaluating support to design [Blessing and Chakrabarti, 2009]. From this perspective, this chapter will argue why the research questions are meaningful *and* relevant, that the ways to answer these research questions are appropriate and *what knowledge* the answers to these research

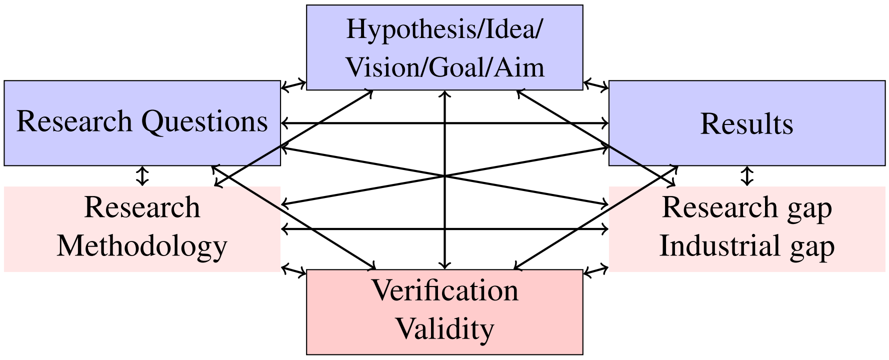


Figure 3.1: The structure of applied research, I am indebted by Dr. Stefan Dahlström for this figure.

questions provide.

A coherent research approach is one where the structure and connections between research gap, research goal, results, verification and validation, research methodology, and research questions support one another to build a whole. This is schematically shown in Figure 3.1.

Design is a human activity concerning the creation of services and/or artefacts. Design has both social and technical consequences and connects to the natural sciences and mathematics as well as more applied fields such as technology. In addition, engineering design involves the interaction of human individuals. Hence, every attempt to understand or influence some aspects in the engineering design process should take these different aspect under consideration, albeit in a varying proportion depending on what is being studied [Hubka and Eder, 1987].

The challenge in design is how to attain the best results possible with respect to quality, design time, life cycle perspective etc. [Hubka and Eder, 1987]. Science, on the other hand, is defined as a knowledge creating activity. Eekels and Roozenburg, contrasts these activities arguing for their likenesses and differences [Eekels and Roozenburg, 1991]. These authors mean that *scientific research* starts with the problem that the available knowledge does not conform to experimental knowledge. The task is then to extend this knowledge so that the experimental facts can be explained. *Engineering design*, on the other hand, starts with a value statements of the world and from these tries to change the world. The authors go on to say that it might happen during engineering design that the world envisioned for the engineering designer might not be feasible or desirable or that it is impossible to know if it is desirable. Here, a recourse to scientific research is needed to fill the gap. Hence, engineering activities resort to research activities when a problem without a known solution is encountered during engineering design to search

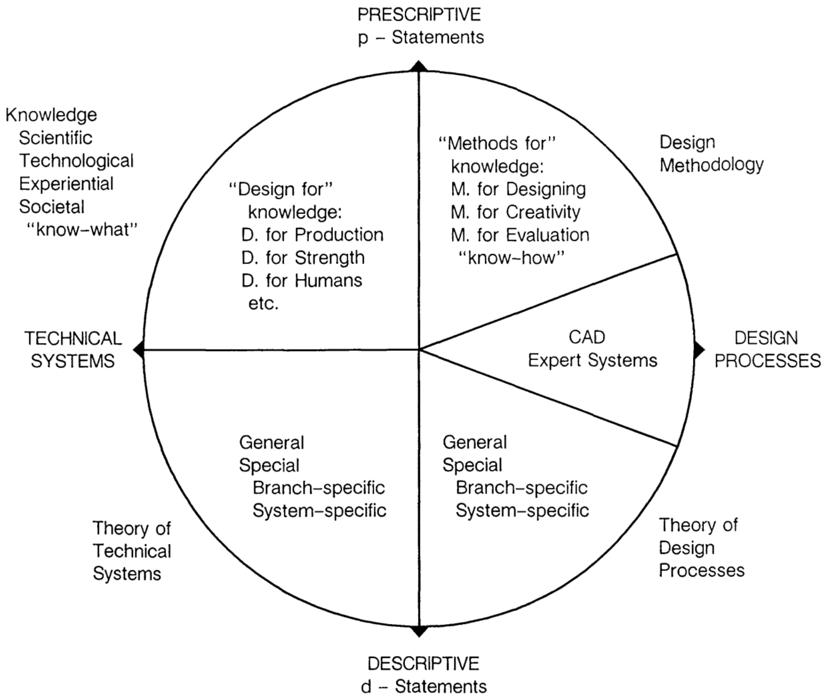


Figure 3.2: Main categories of design science [Hubka and Eder, 1988].

for new knowledge to fill the identified gap. A challenge for this view is that the research gap hinges on the structures or paradigm of the engineering design process.

According to Hubka and Eder [Hubka and Eder, 1988], design science is "...the problem of determining and categorizing all regular phenomena of the system to be designed, and of the design process. Design science is also concerned with deriving from the applied knowledge of the natural sciences appropriate information in a form suitable for the designers use". A representation of the way they structure design knowledge is depicted in Figure 3.2. Here, one dimension contrasts between statements about the designing process and the object, the other between descriptive and prescriptive statements.

Blessing and Chakrabarti also express the view that during design the designers turn to research when there is a knowledge gap encountered. In addition, Blessing and Chakrabarti, while describing research in design science, stress the organization where designing takes place [Blessing and Chakrabarti, 2009]. According to these authors, design science has two objectives:

- "the formulation and validation of models and theories about the phenomenon of design with all its facets (people, product, knowledge/methods/tools, organization, micro-economy and macro-economy); and

- the development and validation of support founded on these models and theories in order to improve design practice, including education and its outcome."

The vast scope of design science makes it easy to understand why the question on how to conduct research within this area has not reached a consensus. Instead a number of methodologies and approaches have been suggested, and, according to Blessing and Chakrabarti "a methodology should be used in a flexible and opportunistic way."

3.1.1 Theoretical perspectives

The research presented in this thesis is closer to the applied sciences than to the social sciences, with the exception of Paper A. In order to understand how the developed methods and tools are embedded in the designing organization, as well as to guarantee the soundness of the qualitative elements of this research, the adopted views on research will be given here.

Critical realism is a candidate for an epistemology for design science. Central to the critical realist is to make abstract identification of structures and mechanisms which, although not directly observable, underlie and govern the events of experience and hence explain why regularities occur (Johnson & Duberley, 2000). However, there is a problem with this stance; how can this structure be proposed and tested against reality in a theory neutral way? An alternative to this stance is pragmatic-critical realism. To avoid the problem in critical realism, inquiry, in pragmatic-critical realism, has as its goal a transformed situation rather than some correspondence with an inaccessible reality. (Johnson & Duberley, 2000). A theory is here adequate if it allows people to interact satisfactorily with their social or natural environments ((Law & Lodge, 1984) cited by (Johnson & Duberley, 2000)), if they cannot, the theories need revision. Using this epistemology, knowledge claims can be evaluated by implementing the practical intervention; and assessing how efficacious the intervention is at achieving the expected outcome (Johnson & Duberley, 2000) (my attention to pragmatic-critical realism in connection to design science is attributed to the work by Forslund (Forslund, 2011)). This stance holds similarities to the design research methodology described below.

Design science is further inherently multidisciplinary. In situations involving individuals it can be hard or impossible to establish structures in a mathematical manner (Johansson, 2003). It is not self-evident what categories to use (Glaser & Strauss, 1967) or how my perspective affects these categories. The philosophical underpinning for studying human activity is therefore often associated with a hermeneutical perspective (Williamson, 2002). On the other hand, design research can sometimes pinpoint a need to model or simulate, to take a few examples, for stochastic or physical phenomena in connection with product realization or the use of better optimization algorithms. The validity or trustworthiness of these models or simulation tools is often based on a philosophical consideration closer to a positivistic standpoint (Williamson, 2002). It should however be noted that for design research, the suggested methods and tools should, if such, be able to be a close enough representation of the structure of reality so that it contributes to worth in the context of designing organizations. These two perspectives have implications on research methodology and research evaluation, see Section 5.4.

3.2 Design research methodology

Blessing and Chakrabarti identified three related issues in design research in need of addressing

- ”the lack of overview of existing research;
- the lack of use of results in practice;
- the lack of scientific rigor.”

Blessing and Chakrabarti go on to propose *Design Research Methodology* ”as an approach and a set of supporting methods and guidelines to be used as a framework for doing design research” ([Blessing and Chakrabarti, 2009], p. 9). DRM is a research methodology consisting of four main phases, see Figure 3.3. It is an iterative methodology and one need not approach the phases in a chronological order. Furthermore, depending on the situation at hand and the maturity of the research area some phases need more attention and others less. Blessing and Chakrabarti point out, further, that it may not always be possible to perform all stages in depth during one research project (Blessing & Chakrabarti, 2009).

Phase 1 is research clarification (RC). The main goal of this phase is to find a success criterion, a criterion to evaluate the outcome of the research. To find the right criterion one needs to gain an understanding of the situation at hand. The main method in this phase is literature studies. Phase 2 is called descriptive study I (DSI). The purpose here is to clarify the understanding of the situation at hand and to highlight the problems. At this point, detailed review of existing literature is made and if the literature reveals an existing gap, empirical studies should be conducted. In addition, DSI should provide a basis for the third phase, prescriptive study (PS). In this phase knowledge of the present situation and existing problems is used to develop methods and tools to improve the existing situation. In design

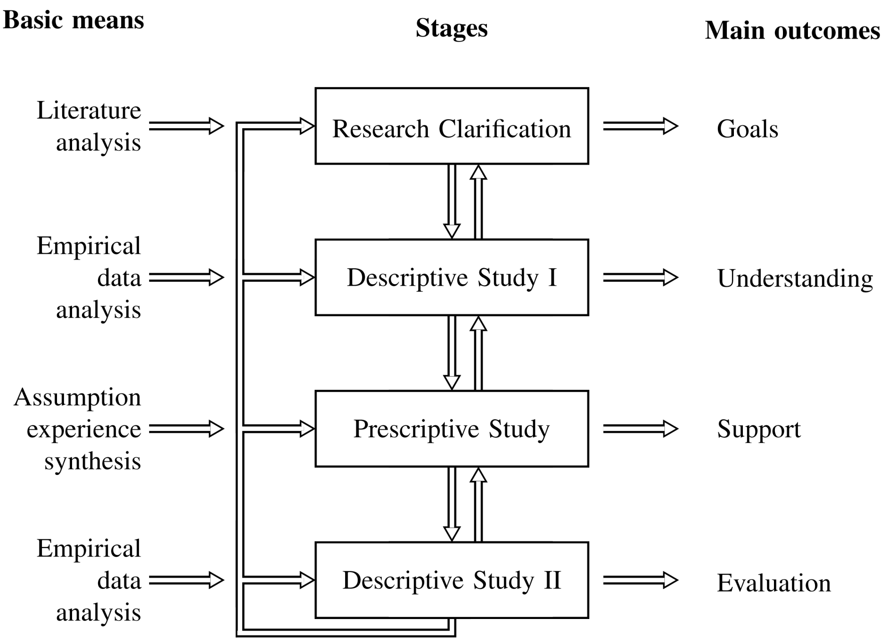


Figure 3.3: Design Research Methodology (DRM) by Blessing and Chakrabarti.

research, every proposed method and tool is in a state of hypotheses until shown useful in context (Almefelt, 2005). The main objective of phase IV, descriptive study II, is therefore to evaluate the contribution of the methods and tools proposed in the prescriptive phase.

3.2.1 Design research methodology in connection to variation simulation and robust design

Blessing and Chakrabarti mean that DRM can be used for individual projects but also for research programs [Blessing and Chakrabarti, 2009]. I will here argue that DRM can be used for the program or paradigm of geometry assurance. A paradigm is a shared view of the research field, which problems are important and what is meant by solving these problems [Kuhn, 1970].

The main issues for proposing a new research methodology for Blessing and Chakrabarti, itemized above, is not applicable to the subarea of geometry assurance. Instead, here it *is* possible to get an overview of existing research and many results are used in practice. Furthermore, the scientific rigor also increases as the field becomes more mature.

DRM as described, seem to correspond with the area of geometry assurance in its earlier less mature state. Here questions like; ”can prediction of variation in the early stages of product development increase the possibility of creating a better product?”, or ”decrease the time to market?” is proper. A support tool could then have bene developed and evaluated in order to support this. However, today, there are a number of simulation tools[1] for variation simulation and they have been evaluated and proven to work in practice, and is often used in practice, see for example [Dahlström, 2005, Maropoulos and Ceglarek, 2010, Lööf, 2010, Wärmefjord, 2011].

Therefore, I am arguing for the legitimacy of identifying research questions to expand the geometry assurance paradigm or of solving problems without known solutions that arise from industrial practice under this paradigm. This is what Kuhn is referring to as normal science [Kuhn, 1970][2].

According to Kuhn, the establishment of a paradigm is a sign of maturity of a research area, and it is this paradigm that enables the more esoteric questions in a field. Normal science is here seen as research based on the results of previous research that leads to a basis for further practice and inquiry. During normal science the paradigm gets further articulated by finding and solving problems whose solutions are unknown.

The paradigm of geometry assurance includes virtual product development, product verification, and production inspection together with requirement management systems and their relations. One difficulty in working in an area that has a clear paradigm is that the research problems and the methods to solve these problems follows a line of reasoning that is dictated by the field. It can therefore, be important to try to articulate the paradigm and to be critical towards it. In the discussion chapter of this thesis an alternative approach for a paradigm will be discussed.

All this being said, I have used a research methodology inspired by DRM as a guidance for the progress of the project, for communication and positioning of research results. However, within a research area with the maturity level of geometry assurance, there is no need to state a ”measurable success criteria” (for example, ”increased product quality” or ”decreased lead time”) for an individual research project. This is instead an evaluation for the accumulated field. This is an important inquiry, but not an inquiry for this project. Instead, a research result is more like answering a questions posed by practitioners within the field, with no known solution.

[1] A compilation consisting of 11 CAT software packages can be found in [Lööf, 2010].

[2] Kuhn is using the term paradigm for research in the natural science. However, the term commonly refers also to other research fields, see for example [Blessing and Chakrabarti, 2009], where it is used in relation to design research. It is, further, possible to use the term ”paraprax” for the industrial use of geometry assurance [Nordin, 1988]. However, I have used the term ”paradigm” to denote both the academic and industrial structure of geometry assurance.

After this detour, the view adopted here shows, again, similarities with the view put forward by Eekels and Roozenburg[3], however, with a critical stance to the existing paradigm.

3.3 Applied methodology

In the previous section a description of the DRM has been given and the perspective taken in using DRM in the area of geometry assurance. As a basis for explaining how DRM is applied in this thesis, the five dimension (1) Research question (2) the DRM stages (3) the published papers and (5) the types of results is used[4]. This is illustrated in Figure 3.4. The larger circle represents a comprehensive study while the smaller circle represents a literature- or initial study.

The focus that guided this research project is identifying phenomena, related to temperature and heat, that is contributing to the effect of variation and developing methods and tools to enable virtual evaluations of non-nominal assemblies concerning these phenomena for the industrial design context. The research criterion is ”enabling accurate evaluation of the non-nominal geometry, including the influence of temperature and heat to support decision making during design.” One important aspect to consider is, therefore, the time required by the evaluations. Here a contrast can be made between research in applied mathematics and product development; if a research result reduces the computational time, the reduction need to be significant for the designer in design research. In contrast, if the reduction in time has no impact for the designer, the result can be important but should be categorized as applied mathematics[5].

RQ 1 aims at an understanding of the situation faced by practitioners regarding the research criteria. This question has been considered in Paper A for products containing plastic parts. Here, an exploratory study is conducted where robustness aspects are collected, categorized and related to other robustness aspects through a developing framework. This framework has been used to identify a number of issues that lack simulation support in design practice. In addition, in Paper I, the effect of temperature and variation was studied in combination with rattle and squeak simulation. Furthermore, in regards to the effect of heat in welding; based on literature study, a need is identified for methods and tools to enable variation simulation for product evaluation during design and to establish its accuracy. This is a prerequisite for further industrial use.

[3]At least ”locally”, meaning that it can happen that the engineering practice changes and with this change follow new challanges.

[4]Inspired by [Forslund, 2011].

[5]I will not, here, try to set up a criterion of how to quantitatively separate the two.

RQ 2 and RQ 3 build in part on the results from RQ 1. Here, literature studies in combination with implementations of methods into software packages and evaluations of case studies are used to draw conclusions. Alternatively, industrial partners are faced with a problem that, after a literature study, is concluded without a known solution.

The shared terminology and methods between researcher and industries is one of the strength of having a matured and shared paradigm. In Paper B, the combination of thermal expansion with variation simulation was studied. In Paper C the same industrial case, used in Paper B, is used for studying induced stresses in the non-nominal assembly. In Paper C, furthermore, a technique was developed, implemented and evaluated for variation simulation of stresses. Paper H was initiated due to a pressing problem of long simulation times for variation simulation for some applications. Here, a method was developed using quadratic programming to solve the contact modelling in the MIC. In Paper I, an industrial case study was used to virtually study the combination of variation simulation, thermal expansion and the phenomena of rattle and squeak. Here, methods and tools developed in Paper B and H were used.

Welding simulation in combination with variation simulation is much less mature compared to the other simulation techniques used in this work. The major challenge in evaluating variation including the variation stemming from the combination of welding distortion and deviation positioning of the parts, is to acquire reasonable results within reasonable computational time[6]. In Paper D a method has been proposed, implemented and evaluated against published simulation and measurement results that have been used as benchmarks. In Paper E, the effect of clamping to reduce the influence of deviation error is investigated. Here, cases with published simulation and measurement results have been compared to welding simulation implementation developed in the context of this research project. These simulation cases were extended to include clamping to evaluate its influence. In Paper F the consequence of non-nominal temperature calculation in the SCV-Method was investigated, and in Paper G the robustness of the SCV-method is investigated.

3.3.1 Types of results

There are four different types of results that form the outcome of this research. These depend on the DRM stages and what is being studied.

[6] Here it is assumed that computational methods can be used for this evaluation. In practice it might be possible for other approaches, such as standard error marginal or skilled professionals, that know how to compensate for deviations.

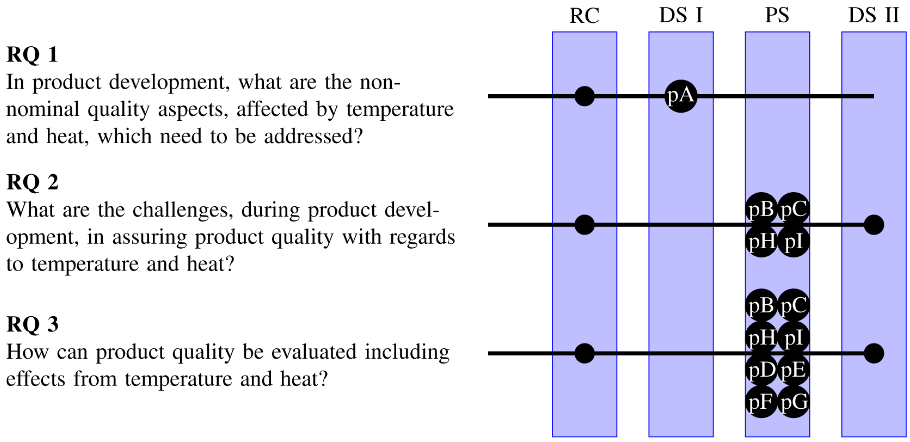


Figure 3.4: The distribution of Paper A-I in the context of DRM.

1. *A framework of descriptive studies*. The descriptive study presented in Paper A resulted in a framework of levels of robustness in connection to design of products that include plastics. This framework is based on existing theoretical foundation and empirical findings.

2. *Descriptive results*. In Paper A interpretation of the empirical data led to findings in the design practice.

3. *Prescriptive methods and tools*. The formulation and validation of method and tools forms the largest part of this work and appears in Papers B, C, D, F, G, and H.

4. *Knowledge of phenomenon connected to design*. Including the effect of temperature and heat while evaluating variation has led to a number of observations regarding phenomena that have implication on the geometry and quality during the product life cycle.

3.3.2 Methods used

As is mentioned above, design science involves the perspective of the designers and an understanding of how designing is conducted as well as elements from the applied sciences. The research methods used vary, therefore, according to the object/perspectives studied. Here is a list of methods used.

Literature studies

To have an understanding of the existing body of literature is one important prerequisite in any research. In all appended papers literature studies have been conducted in order to position proposed methods, tools or framework.

Hypothetico-deductive method

In the prescriptive study the main focus is on developing new methods and tools. In this phase it can be hard to pinpoint what activities lead to an idea or conclusion. As with every research activity the development of methods and tools should be based on assumption and experience from related areas. However, arguably, the process from assumption and experience [Blessing and Chakrabarti, 2009] to proposed methods and tools is not very clear. However, based on existing literature and understanding of the design process and the object to be designed, including the product realization phase, an hypothesis can be formulated.

In Paper B, the hypothesis is that integration of thermal expansion with geometrical variation is not additive. In Paper C the hypothesis is that the MIC can be extended to include evaluations of stresses in the non-nominal assembly. In paper D, F, and G there are hypotheses on how to simulate variation in combination with welding and paper E includes a hypothesis on how clamping can decrease the effect of variation on weld induced deformation.

Finally, in Paper I, the hypothesis is that thermal expansion influences the result for non-nominal rattle and squeak evaluations. These hypotheses can be corroborated or rejected using induction. This is the hypothetico-deductive method [Johansson, 2003].

Interviews - Paper A

An interview study was performed, concentrating on five Swedish companies working with plastics design or simulations. Specific focus was set on the ability to actually achieve robust products through current simulation practice. The following questions were addressed: (1) What variation simulation tools are used at the companies and what different types of robustness do they address? (2) Are there relevant variation management issues that lack simulation support? (3) What are the prerequisites for using variation simulation as design support at the company? A total of 17 persons were interviewed through semi-structured interviews: 7 persons from a mobile telecom company, 5 from an automotive company, 4 from two different plastic component suppliers and one person from an injection molding simulation software company.

Coding techniques - Paper A

A procedure of coding described in grounded theory [Glaser B, 1967] was used on the observations made in connection with Paper A. During the data collection a constant memo writing and comparing of results was conducted in order to categorize the observations related to the focus.

CHAPTER 4

Results

This chapter will provide a summary of the results gained during the work that formed the basis for the appended papers in this thesis along with a discussion of their interconnection.

4.1 Investigating the role of simulation for robust plastic design

In Paper A, the main focus is to identify opportunities to increase the robustness of plastic design through computer simulations. In an effort to understand the designing process and the current challenges, an interview study was conducted with five participating companies involved in design or simulation of plastics. In connection with this study, a framework for robust design for plastics was developed. Using this framework, the interconnection of activities related to robust plastic design was identified. By relating current practices to this framework, a number of areas were identified that could enhance the practices.

4.1.1 A framework for robust plastic design

The framework for robust plastics design is based on the notion proposed by Smith and Clarkson [Smith and John Clarkson, 2005]. According to these authors, in robust design the aim is to break the connection between contextual and formal and between formal and functional variation (see Figure 2.6). The resulting framework is illustrated in Figure 4.1. Here, the interconnection between different stages of robustness is illustrated together with associated design activities. Geometric robustness is therefore divided into: part robustness; the ability of a part in terms of part geometry and materials, along with tool design properties and process parameters, to suppress variation in the noise parameters (raw material, process and tool

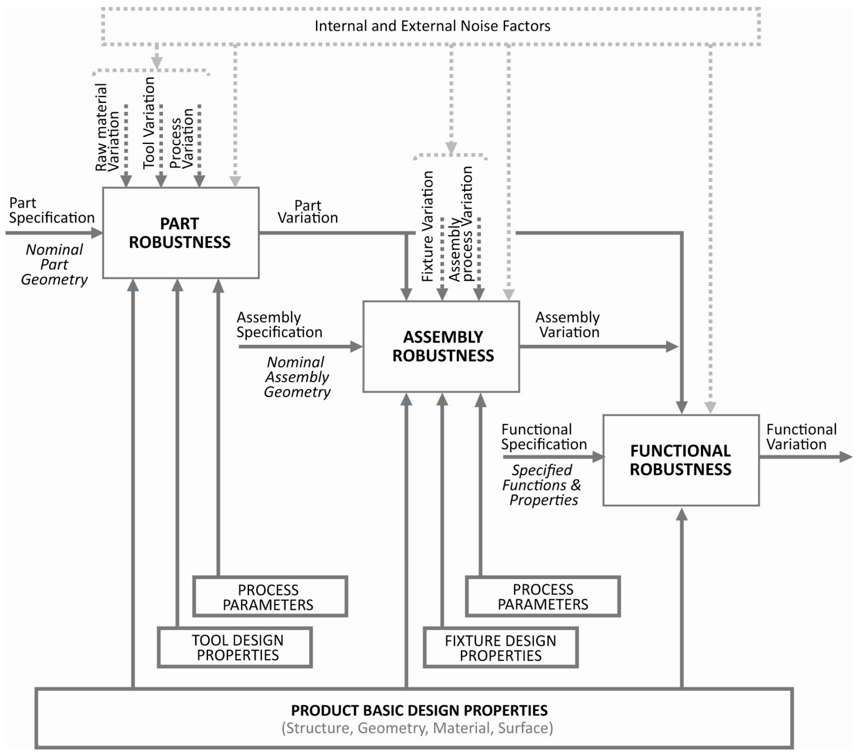


Figure 4.1: Framework to study geometric robustness for plastic design [Lorin, 2010].

variation). Assembly robustness here means the ability of the assembly design in terms of parts and their relations to minimize the effects of variation. Relevant factors are locator positions in combination with part geometry and assembly structure (see [Söderberg and Lindkvist, 1999]). At this stage part variation is a noise factor along with fixture and assembly process variation. Finally, functional robustness is the ability of the assembled product in terms of the overall connection between the behavior of physical parts and relations and the desired functions and properties, to minimize variation in functions and properties. Part and assembly variation are regarded here as noise factors.

4.1.2 Identified issues

The framework, presented above, was used to position and identify issues from the interviews. Identified functionality that could enhance computer tools in attaining robust plastic designs include

- Improved functionality for simulating part variation for plastic components.

- Enhanced functionality for non-rigid variation simulation of plastic components, including support for modeling different physical fasteners as locators, non-linear stress-strain relationships and process effects such as residual stress and fiber orientations.
- The ability to include effects of thermal expansion within CAT.
- Additional support for exporting CAT results to analysis tools such as structural analysis.

4.2 Combining variation simulation with thermal expansion simulation for geometry assurance

One difficulty identified in Paper A is the lack of routines and computer tools to assure the functional robustness of the product in its environment of use. One specific robustness aspect expressed by the interviewees is a lack in computer support in evaluating non-nominal thermal expansion in the user phase. Thermal expansion is a phenomenon present in almost all materials. For many polymers thermal expansion can be significantly higher than for metals.

4.2.1 Combining assembly variation and thermal expansion

In Paper B, a method to combine the virtual evaluation of the combination of variation and thermal expansion was implemented in RD&T, see Section 2.6, which is considered a standard software tool used in industry. Together with practitioners from an automotive company, an industrial case study was chosen. The automotive company was interested in how to determine, quantitatively, the nominal gaps to allow for thermal expansion and in ways to evaluate alternative approaches to assure the geometric quality at different temperatures. It was shown that assembly variation depends on the thermal expansion. Hence, in order to predict accurately assembly variation of produced units, thermal expansion needs to be considered.

4.3 Variation simulation of stresses using the method of influence coefficients

During the work with the case described in Paper B, alternative means of handling thermal expansion was proposed and investigated. The question was raised; what are the stresses introduced in the non-nominal assembly at different temperatures and how can these be evaluated. Using FEM, it is a standard analysis process to evaluate the induced stresses given certain loads. However, the long simulation times involved in a typical FEM simulation makes this unfeasible for MC based variation simulation.

4.3.1 Variation simulation of stresses

In Paper C, the MIC, commonly used in variation simulation for deformation is extended to include calculation of stresses. This enables the evaluations of stresses in the non-nominal assembly in a fraction of the time required for FEM. The method was evaluated against the commercial FEM-software, Femap, giving a reasonable agreement. Furthermore, the industrial case used in Paper B, was extended and used to elicit the use of the method. One difference between the cases presented in Paper B and Paper C is that in Paper C the maximum temperature is reduced to 60°C. This is a limitation in the obtained material data, relating stress and strains, of the applique. For this early design evaluation, it is here not considered a limitation.

Interesting enough, a paper presented at the conference where Paper C was initially published, presented another approach for evaluating the von Mises stresses induced by non-nominal assemblies [Jaishankar et al., 2013]. This approach is, however, based on tolerance-Maps and it is not easy to see how this can be extended to more complicated industrial cases or how to include thermal expansion.

4.4 Variation simulation of welded assemblies using a thermo-elastic finite element model

In Paper D, the focus is on methods to evaluate robustness for continuous welds. This need has been identified in earlier research [Wärmefjord, 2011]. Welding simulation in the context of variation simulation is much less developed compared to rigid and non-rigid variation simulation, see Sections 2.6 and 2.10. Therefore, the focus here is more on developing methods and evaluating these. This is a prerequisite for prescriptive methods and tools for the industrial context.

4.4.1 Steady-state Convex hull Volumetric shrinkage-method

In this paper, a method called the Steady-State Convex hull Volumetric shrinkage-method (SCV-method) is developed consisting of 3 steps, see Figure 4.2:

1. The first part is a steady-state heat calculation at a position along the weld path.

2. A convex hull is then formed as a 2D- projection of the nodes above the melted temperature onto a plane, with normal pointing in the direction of the weld, that is swept along the entire welding path. This is done for all welds.

3. Finally, an elastic volumetric shrinkage calculation is performed, based on the melted volume, which is defined by sweeping the convex hull along the weld path.

As described above (Section 2.10.3), there are several methods to simulate weld-induced distortion based on applied strain. One advantage of the volumetric approach is that the effects of variation on the melted zone can be included. How the inherent strain or the model by Camilleri et al. are affected by variation in different parts of the geometry is not known. The SCV-method is evaluated against transient simulation and measurements [Deo and Michaleris, 2002] and the combination of variation simulation and welding simulation [Pahkamaa et al., 2012] giving reasonable results. Furthermore, in [Pahkamaa et al., 2012], only the combination of variation in position and weld-induced deformation is considered while in Paper D it is only variation in the weld-induced deformation. Therefore, the calculation of variation in weld-induced deformation for the transient case has been performed and displayed in Figure 4.3. Here Goldak's double ellipsoid has been used as heat source and the material is "A36-steel". The process parameters and the mesh are described in Paper D.

The SCV-method has been applied, also, to a laser welded butt-joint assembly described in [Tsirkas et al., 2003] and studied in Paper E. Here a cone is used as heat source, the material is again A36-steel. The process parameters and the mesh is described in Paper E. In Figure 4.4 the application of the SCV-method is compared to transient welding simulation, here under nominal condition, giving good agreement. These simulation results are, further, in good agreement with the simulated and measured values in [Tsirkas et al., 2003].

4.5 Welding simulation of non-nominal structures with clamps

One question arising when considering the effect of position deviation on welding deformation is; is it possible to find means for decreasing the effect of variation so that variation simulation and welding simulation, even though combinatorial effects are present, do not need to be considered during product development? In Paper E, one strategy using clamps is evaluated. Here, after the parts to be welded are positioned, clamps are used to force these parts in a position as close to

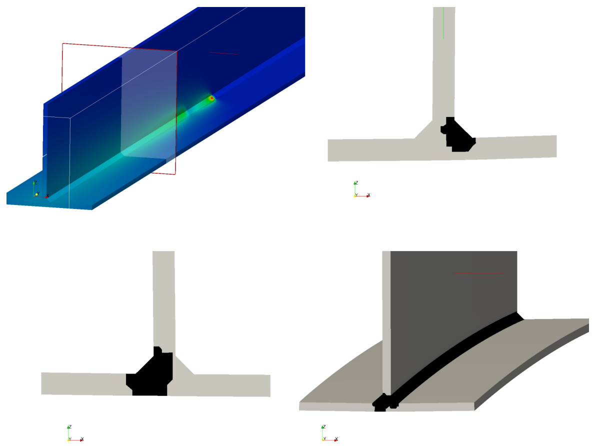


Figure 4.2: The 3 major steps in the SCV-method: steady-state thermal analysis, computation of two-dimensional melting region and applying thermal load to the three-dimensional model.

nominal as possible. This will reduce the deviation of the weld path, but introduce initial stresses in the assembly.

Two case studies were performed using full transient welding simulation. It was here further corroborated that position errors influence weld-induced deformation. And although the use of clamps had a small influence on the deviation, it did not remove the influence from position errors. The conclusion is that this strategy cannot be used to remove the effect of variation on the weld-induced deformation. Hence, the hypothesis that variation simulation is needed also if clamping is used cannot be rejected. Although further research on the application of clamps on non-nominal welding is needed; in order to assuring the geometry of welded assemblies, variation simulation and welding simulation need to be considered together.

4.6 Simulation of non-nominal welds by resolving the melted zone and its implication to variation simulation

The SCV-method presented in Paper D, is extended in Paper F. In the original SCV-method only one steady state heat calculation is used to approximate the convex hull determining the geometry of the melted zone. This is a good approximation if the geometry and material surrounding the weld path is not varying

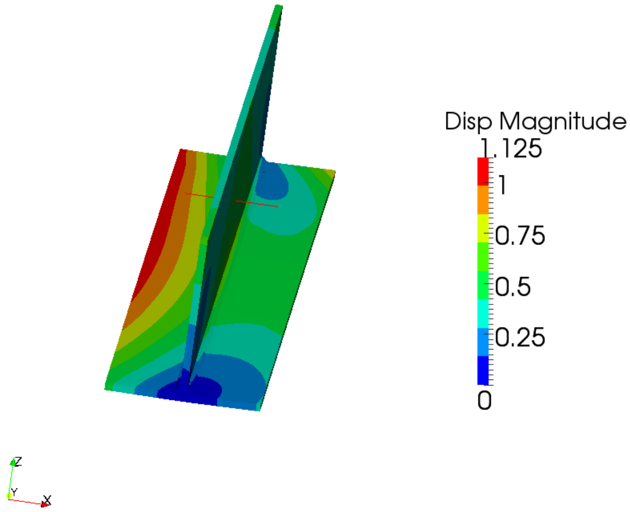


Figure 4.3: Variation of weld-induced deformation for a transient MC run consisting of 37 iterations.

along the path. If this is not the case, for example if the distance between the parts surrounding the weld-joint are varying due to positioning error, the melted zone along the welded path could vary along the path.

In Paper F, transient welding simulation is used to show that the melted zone does vary in the presence of variation. Therefore, the SCV-method is extended using several steady state heat calculations to define the convex hull, corresponding to a weld path, as a convex combination of several hulls. It seems that the melted zone is better approximated using this approach and that it influence the deformation and variation results. However, more research is needed to conclude how this variation corresponds to the variation in real welds.

4.7 On the robustness of the volumetric shrinkage method in the context of variation simulation

The SCV-method is further investigated in Paper G where the robustness of the SCV-method is investigated for small perturbation which is essential to variation simulation. Here, instead of having a single consisting mesh, see Section 2.7, every part, that is all the parts plus the filler material has its own mesh and the parts are fixed relative to each other through bound contacts. This is done to enable larger positioning errors without affecting the quality of the mesh. Furthermore, in this study the parts are only allowed to move along the intersecting boundary of the adjacent parts and the filler material. This restriction is not applicable to variation simulation in general but is used here for the numerical investigation.

It is shown that the SCV-method as applied here is sensitive to small perturbations. To address this lack of robustness a modification of the SCV-method is proposed. In the original SCV-methods the nodes that are above the melt temperature are used to define the melted zone. A better approximation would be to allow the melted zone to be defined independently of the mesh. The modification proposed in Paper G consists of finding the volume inside each element that is melted. An optimization problem is formulated to find a set of node temperatures so that the melted volume is preserved. Using regression analysis it is shown that the relation between the translation in the traverse direction and maximum deformation was present to a higher degree in this modified method. However, there are still effects that are probably due to inaccuracies in the bond contacts.

4.8 Efficient contact modeling in non-rigid variation simulation

During non-rigid variation simulation it is important to consider the contact forces between parts, see Section 2.6.2. For variation simulation where thermal expansion is considered, or other assemblies with complex contact surfaces, many contact points may be needed in order to obtain accurate results. This can be very time consuming. This problem was identified as an obstacle for being able to simulate the models needed for the virtual product development used at one of the industrial partners for this project.

Presented in Paper H is an approach to solve the contact modeling problem in every MC-iteration using MIC, as a quadratic programming problem. This approach has its root in FEM but is here formulated in the context of the MIC. It was shown that this approach could reduce the simulation times many times over compared to previously used methods in variation simulation.

4.9 Squeak and rattle simulation with consideration to temperature using E-LINE^{TM} method and Monte Carlo based variation simulation

In Paper I the combination of thermal expansion with variation simulation is studied within the application of rattle and squeak. Rattle and squeak simulation is a relatively new phenomena to be studied in virtual product development, see [Weber and Benhayoun, 2010, Weber and Benhayoun, 2012] and [Weber et al., 2013]. Rattle and squeak are phenomena that arise from vibrations, for example in automobiles driving on an uneven road. Rattle is the noise stemming from adjacent parts that clash and squeak is noise stemming from friction between parts in contact with a relative motion.

It is known that rattle and squeak is dependent on temperature but it is not known how to include temperature effect while simulating rattle and squeak. Since thermal expansion and positioning error will influence the geometric relation between parts, this is a phenomenon of interest to study in combination with rattle and squeak.

The study reported in Paper I, involves an automobile center stack panel, see Figure 4.5. The study included effect of temperatures by considering thermal expansion and the temperature dependence in material properties in variation simulation and in transient simulation. The result showed that including these temperature effects had a significant impact on the simulated outcome. However, these results need to be compared to experimental results of rattle and squeak for validation.

4.10 Positioning the results in the framework of robust plastic design

In this section the results are positioned in the framework developed in connection to the study presented in Paper A, see Figure 4.1. The Framework was originally developed for plastic design but is here used to communicate how the results can be used to increase the robustness of generic products.

In Paper B and C the combination of non-nominal assembly in combination with thermal expansion is studied. These address a combination of assembly robustness and functional robustness by studying how manufacturing inaccuracies affect the intended properties of the product during use. Part variation is here considered an input.

Papers D to G deal with assembly variation stemming from welding. This is using simulation aimed at increased assembly robustness.

The contact modeling addressed in Paper H is a general result of variation simulation and can be used both for assembly robustness- and functional robustness simulations or a combination of both.

Finally, the non-nominal rattle and squeak simulation in combination with thermal expansion addressed in Paper I is, again, focusing on the combination of assembly robustness- and functional robustness simulation.

For the papers addressing several stages of robustness, it is important to note that it is possible to break the connection to find robust solutions in one stage independent of the other. To take one example; in finding a solution that is robust towards rattle and squeak one strategy is to search for a design that avoids rattle and squeak independent of the assembly variation. This might be achieved by putting large distances between adjacent parts, say, or designing for structural properties to suppress the magnitude of the dynamic response. Another strategy is to assure the quality of rattle and squeak for the physical products that are close to nominal and focus on the robustness of the assembly. The third alternative is to search for a robust solution in several levels of robustness simultaneously. Hence, by combining several levels of robustness it is possible to investigate a larger fraction of the design space by considering different means for a robust solution.

4.11 Industrial implementation of research results

Many of the results presented in this thesis have been researched in close collaboration with industrial partners. Also, results have been implemented in demonstrators that have been shown and discussed with representatives from many industries. For research in product development industrial implementation is an important part in evaluating the research result [Blessing and Chakrabarti, 2009].

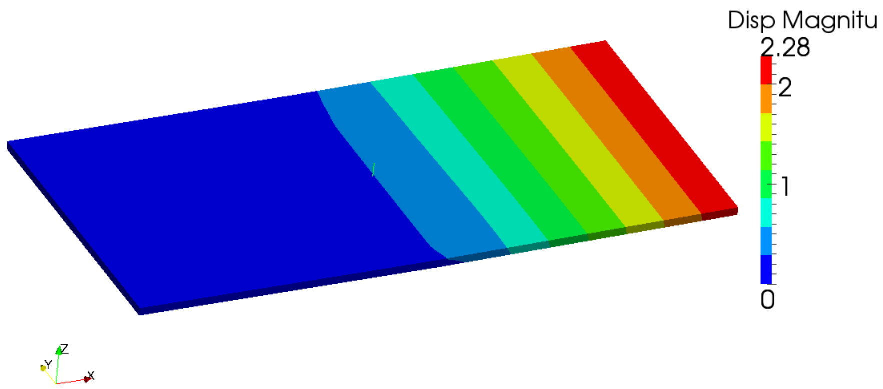
- Paper A: This is a descriptive study involving 5 Swedish companies; 1 mobile telecom company, 1 automobile company, two different plastic component supplier and 1 injection molding simulation software company. The result affected the continuation of the research project.

- Paper B: Tested on industrial cases and implemented in a commercial software used at a number of industrial companies.

- Paper C: Tested on an industrial case and implemented in a demonstrator. Is being implemented in a future version of a commercial software.

- Paper D-G: Not yet implemented or testes on industrial case studies.

- Paper H: Tested on a number of industrial case studies. Implementation in a commercial software is planned.
- Paper I: Tested in an industrial case study. During this case, the method that was implemented in Paper B was used. However, a number of smaller issues specific to the rattle and squeak application was identified and implemented during the work on the case.



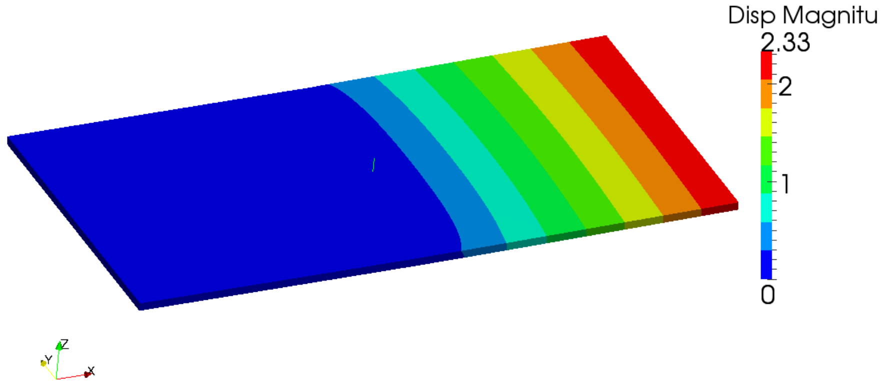


Figure 4.4: A laser welded butt-joint. Above is the result from a full transient simulation and below the SCV-method is used.

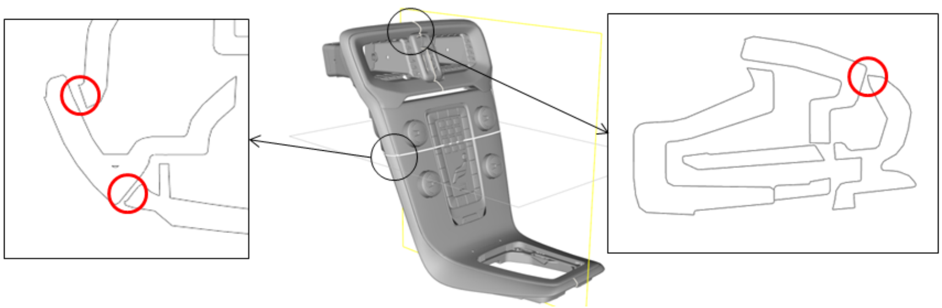


Figure 4.5: A center stack panel for a car that is used as a case study to investigate the combination of non-nominal thermal expansion with rattle and squeak.

CHAPTER 5

Discussion

In this chapter, the results will be discussed in connection to the research questions, the research approach and verification and validation. In addition, the applicability of the research approach will be examined. Finally, the scientific and industrial relevance will be discussed.

5.1 Answering the research questions

RQ 1 *In product development, what are the non-nominal quality aspects, affected by temperature and heat, which need to be addressed?*

Critical measures can be affected by temperature. There are cases where the effect of thermal expansion is comparable in magnitude to part and assembly variation, depending on temperature range and material. This was known prior to this work. This effect is, however, shown to be non additive, i.e. it is not simply possible to consider part- and assembly variation and add thermal expansion to the result. For plastic materials, the combination of part- and assembly variation and thermal expansion can lead to plastic deformation and material degradations. It is therefore important to assure that the stresses in the temperature span are below critical levels for the non-nominal product.

It is known that rattle and squeak are dependent on temperature. During the virtual rattle and squeak evaluation it has been shown that both non-nominal thermal expansion and the temperature dependent material properties is influencing rattle and squeak.

For welded assemblies positioning errors and weld induced deformation is not additive. This is not a result from this research project but it has here been corroborated. The combinatorial effect can be present also when clamping is used to suppress variation.

RQ 2 *What are the challenges, during product development, in assuring product quality with regard to temperature and heat?*

The typical challenge for robustness evaluations is how to acquire an accurate approximation of the statistical results within reasonable time. MC-simulation, which is used in this work, requires quite a number of iterations, see Section 2.5.3. The MIC used for variation simulation can be extended to include thermal expansion in a straightforward fashion[1]. How to simulate the statistical distribution of stresses was, on the other hand, not known. Another challenge when consider thermal expansion in combination with variation is that the contact between parts can increase leading to more complex contact conditions. Here, contact algorithms used in MC-simulation, in some cases, lead to very long simulation times. For welding simulation, the situation is similar. Here, simulation times of hours are not uncommon. Therefore, it is a challenge to simulate the combination of variation and welding deformation in the development phase.

RQ 3 *How can product quality be evaluated including effects from temperature and heat?*

The challenges identified in RQ 2 work as input to find solutions to improve the capability to evaluate product quality.

Starting from the MIC used for geometric variation, it is possible to create a sensitivity relation between deviation in the locating point and the 9 stress component for a critical point. Once the sensitivity matrix is known, the distribution of the stress components can be calculated in a similar fashion as the ordinary MIC. Given the distribution of the stress components, it is a simple operation to transform the stress component to a stress invariant that can be evaluated.

In order to model the contact between parts in MC-simulations, using the influence coefficients, it is possible to formulate a quadratic programming problem that is solved in every iteration. There exists efficient algorithms to solve this problem and for complex contact situation, the simulation time can be greatly reduced. This enables more accurate statistical results and enables the possibility to evaluate more design options. In addition, the solution to the contact problem has an interpolation as a minimum of the potential energy. The earlier method based on heuristic methods to find the contact forces between parts in variation simulation do not have a mechanical interpretation. Therefore, this method in some cases may also be a closer representation of reality.

To approximate and evaluate the effect of variation on welding deformation

[1]This is valid for assemblies that is not welded or glued

the SCV-method can be used with reasonable accuracy, see Section 4.4.1. This method is based on volumetric shrinkage. There are other approximate methods to evaluate weld induced deformation but the advantage of the volumetric method is that it is possible to relate the melted area to the temperature distribution during welding. Therefore, it is possible to relate variation in the melted area to positioning errors of the parts prior to welding.

5.2 Evaluating the quality of the research result

The different types of results in this thesis call for different approaches in evaluating its quality. As described in Section 3.3.1 the types of results are; 1) A framework of descriptive studies 2) Descriptive results, 3) Prescriptive methods and tools, 4) Knowledge of phenomenon connected to design. The different kind of results call for different approaches for evaluate the quality.

In evaluating the quality of research, verification and validation are important terms. Validation and verification refers respectively to internal consistency and justification of knowledge claim. However, these terms are interchanged in the modeling field [Pedersen et al., 2000]. Therefore, in Section 5.2.2 and 5.3 verification and validation is used in the ordinary sense while in Section 5.2.1 the use of the terms follow the praxis of modeling literature.

5.2.1 Research quality in prescriptive methods and tools

In the work of implementing methods and tools a number of benchmark cases have been used verify that the methods have been implemented correctly. This has been done by comparison of other commercial software packages or published results to ensure that what is intended to be implemented has been implemented.

Pedersen et al. suggested that for methods in engineering design " knowledge validation becomes a process of building confidence in its usefulness with respect to knowledge". They therefore suggested the validation square for the validation of design research, see Figure 5.1 [Pedersen et al., 2000].

- In the first square, structural validity is upheld by (1) accepting the constructs validity i.e. use literature, name of the author and publisher to build up confidence in every construct of the proposed method and (2) Accepting method consistency i.e. to build confidence in the relationship between constructs. Method inconsistencies are the generation of information that is inadequate or not necessary.

- Empirical structural validity is supported by (3) accepting the example problems chosen for the validation of method performance. It should be shown

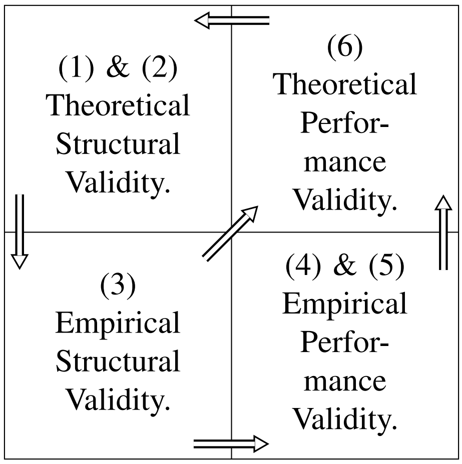


Figure 5.1: Validation square by Pedersen [Pedersen et al., 2000].

that the example problem is i) similar to problems where each construct is generally accepted and ii) that the example problem is similar to the intended problem and iii) that data from the example problem can support a conclusion.

- The empirical performance validity is shown by (4) accepting usefulness of method for some example problems, that is to build confidence of the usefulness of the method through example problems and (5) Accepting that the usefulness is linked to applying the method.
- The last square deals with theoretical performance validity through (6) accepting the usefulness of the method beyond example problems. Generality is assumed through induction by referring to (1)-(5) above.

1. **Accepting the constructs validity**: The methods used in Paper B-I consist of constructs that are widely used in engineering; FEM, MIC, contact modeling, optimization techniques and regression analysis.
2. **Accepting method consistency**: In Paper B thermal expansion using FEM is used together with MIC. Under the assumption of linear material model, small displacements and rotations, thermal expansion is equivalent to a force field. Further, the size of the distortion due to thermal expansion is within the order common in variation simulation using MIC.

   In Paper C the same assumption is placed on the material model, displacements and rotations, as in Paper B. Hence, no conflict is introduced.

The method proposed in Paper D consists of small rotation, heat transfer and volumetric shrinkage. One of the reasons for using the volumetric shrinkage method is that it is, as stated above (Section 4.4.1) based on assumptions of the melted area. This is because the heat transfer is assumed valid also in non-nominal welding simulation.

In Paper E transient welding simulation is used in combination with deviation in fixtures and clamping. Transient welding has been used previously with deviation [Pahkamaa et al., 2012] and clamping is a standard technique to impose boundary conditions that constrains the parts to be welded in more than 6 degrees of freedom. It is assumed that clamping and deviation together with welding does not introduce any conflict.

No Further relations are introduced in Paper F-I.

3. **Accepting the example problem**: The acceptance of example problems in Papers B, C, and I is based on careful considerations together with industrial partners. The example problems used in Paper H are further based on problems where previous methods have been inadequate. Papers D-G deal with welding. The combination of variation- and welding simulation is less mature and is not used in practice. Here, example problems are chosen on the basis of 1) there exist published measurements and 2) there are material models that are well described.

4. **Accepting usefulness of method for some example problems**: In Papers B, C and I the usefulness is accepted by showing that the result is dependent on the temperature within the tolerated temperature span. Furthermore, the effect of temperature is in magnitude similar to other effects analyzed in variation simulation, with the exception of the stress simulation in Paper C. Here, instead, the usefulness is accepted based on a comparison to yield criteria of the material.

   For the welding application in Papers D-G we again observe that the combination of variation and welding has implication of the results. Industrial implementation and measurement of the methods could further corroborate the usefulness of methods.

5. **Accepting that the usefulness is linked to applying the method**: This is linked to the discussion in Section 3.2.1.

5.2.2 Research quality in a framework of descriptive studies and knowledge of phenomenon connected to design

The verification of these research results follows Buur [Buur and Andreasen, 1990]. Buur recognized that it can be difficult to verify research results in a designing context since there are so many influencing factors. He suggested instead that research in design should be verified by *logical verification* and *verification by acceptance*. By logical verification, Buur means that the theory or framework should have

- **Consistency**; there are no conflicts between individual elements in the theory.
- **Completeness**; all relevant phenomena observed previously can be explained or rejected by the theory.
- **Coherence**; well-established and successful methods agree with the theory.
- Cases and specific design problems can be explained by means of the theory.

The results discussed under this heading are based on well-established and tested theories. Confidence in consistency, completeness and coherence is gained through reviewing existing literature and discussions with experienced designers. Furthermore, the framework proposed in Paper A was continually tested and refined with regard to the four points of logical verification listed above.

Verification by acceptance is:

- Statements of the theory are acceptable to experienced designers.
- Models and methods derived from the theory are acceptable to experienced designers.

The results from this research have been discussed with experienced designers; it has been presented and demonstrated for other researchers and for persons in the industry. Finally, the appended papers have been reviewed and accepted for publication.

5.3 Research quality in descriptive results

When researching the descriptive elements of this research a qualitative approach has been used. This is to ensure the perspective of practitioners of design. To ensure validity includes 3 steps [Yin, 2009].

1. **Internal validity**; ensuring the conclusiveness of the results. That is confidence in relations between conditions. In the descriptive study presented in this thesis, the interest is the perspective of the interviewed practitioners. Therefore, internal validity comes from their ability to communicate their perspectives to the researchers.

2. **External validity**; setting and assuring the domain of generalizability of the results. The result of the study is mainly directed to the investigated companies and is not assumed directly generalizable.

3. **Construct validity**; deals with the extent to which measures used are measuring what they are designed to measure. The object of analysis relates to the studied companies. Here we have been interviewing the relevant practitioners and often the interviewees have recommended other practitioners to interview. Together with a continuous structure of coding procedure of the results until saturation, we gain confidence in the completeness and correctness of construct validity. Furthermore, the manuscript have been reviewed by the interviewees.

Another important quality criteria is

4. **Reliability**; demonstrating that the operations of a study can be repeated with the same results. What has been studied are the participating companies at the time of the investigation.

The semi-structured interview form can influence the researchers in what questions are raised and in what order. In addition, the coding procedure can in some measure be influenced by the researchers. Therefore, there can be some differences in results when compared to those of another set of researchers who performed the study. However, the nature of the descriptive study is close to what is being described, therefore, the main result is likely to be similar.

5.4 Evaluating the coherence of the research approach

In this section, the coherence of the research approach will be discussed with reference to Figure 3.1. It is recognized that it is not possible to make a clear distinction between the research elements and their relations but here it is used as a ground on which to discuss the coherence of the research approach.

The scientific goal is to provide knowledge about the challenges related to quality- or the process of assuring quality of products, when considering temperature and heat. Also, with knowledge of these challenges, methods and tools are developed and evaluated with the aim to increase the quality of products. The industrial goal is to create an awareness of the quality issues related to temperature and heat and to provide means for addressing them in the design process. These are based on the scientific- and industrial gaps regarding knowledge of- and methods focusing on the combination of variation and temperature and heat. The goal and gap are input to formulating the 3 research questions. How the goal, gap and research questions are related to the research methodology was expounded at length in Chapter 3. The research result is, of course, dependent on the gap, goal and research question, and also in the opposite direction; the result has affected the goal and research question as described in Sections 1.4 and 3.3.

The discussion in Section 3.2.1 relates to the relation between the scientific goal and verification and validation. It is, furthermore, important to assure that the process of validation and verification can give answers to the RQs. This is assured by recognizing that to answer the different RQs different types of results with different approaches to verification and validation are required, see Section 3.3.1. The validation, see Section , is designed to build confidence in the usefulness to close the research gap. Finally, the relation between research methodology and verification and validation was expounded in length in Section 3.3, where it is argued that the maturity of geometry assurance and robust design makes it possible to justify knowledge claim if it is possible to claim proximity between reality and simulation on industrial cases.

5.5 Further discussion on the research approach

After evaluating several research approaches in design science, the research activity in this research was identified as mainly "normal science" [Kuhn, 1970] within the paradigm of geometry assurance. One possible criticism of this approach is; would the result have been different using another approach? Or does the reliance of the prevailing paradigm lead to an uncritical research approach?

A justification of using the paradigm of geometry assurance is; first, to clearly articulate the prevailing paradigm does not necessarily lead to an uncritical assumption of the standard praxis. Instead, to clearly state the paradigm makes it easier to question it. Second, the close collaboration with industry in identifying research challenges is closely related to the geometry assurance praxis. This naturally set some boundaries on how to conduct research addressing these research gaps. Thirdly, as pointed out by Blessing and Chakrabarti [Blessing and Chakrabarti, 2009], the background and interest of the researcher does influence the outcome of the project.

In Paper A, the question is posed; "How [is it possible to] combine synthesis activities, supporting the creation of robust concepts, but not necessarily supported by simulation tools, with a simulation procedure?" Following this interesting approach would lead to a research project much different from this project, and possible results that would challenge the current industrial praxis. However, considering my background in physics and mathematics, this approach seems unfeasible for this project.

5.5.1 Research in close collaboration with industry

One aspect of doing research in close collaboration with industry is the advantage of being able to test method, tools, and ideas in the context for which they are designed. A further advantage is that of being presented new ideas for which research results from the project are relevant. This was the case when combining thermal expansion with rattle and squeak in Paper I. The drawback is that for research that is not as used or matured, it can be difficult to test cases in an industrial setting, considering the time and money that need to be invested. This has been the case for the results regarding welding. However, industrial cases are planned.

5.6 Scientific contribution

When conducting research within product development there should be both scientific as well as industrial relevance. The scientific contributions include

- A framework for describing different types of robustness.
- A number of identified robustness issues lacking simulation support.
- New knowledge on how variation depends on the temperature.
- A developed method to simulate the stress stemming from variation and temperature.
- A developed method to evaluate robustness for welded assemblies.
- Increased understanding of the effect of the combination of variation and weld induced distortion using clamping.
- New knowledge regarding the robustness of the proposed SCV-method.
- A new method for contact modeling in variation simulation.
- Increased understanding about how thermal expansion is influencing rattle and squeak evaluation.

5.7 Industrial contribution

The industrial contributions from this work is stated in Section 4.11 but summarized here:

- Increased knowledge about how temperature affects variation regarding aesthetics, stresses and rattle and squeak evaluation can potentially lead to new product solutions and increased quality.
- An implemented tool to study the combination of thermal expansion and variation lead to increased possibility to evaluate the geometric quality during the product life cycle.
- An implementation of a method to study variation of stresses and a new method for contact modeling in variation simulation. These implementations have been used for industrial cases. These implementations are not in the current commercial version of the software where it has been implemented. However, these implementations are planned.

CHAPTER 6

Conclusions

This chapter will present the main conclusion that can be drawn based on the results in this thesis.

6.1 Conclusion

In this work the effect of temperature and heat on quality during production and use have been explored. Focus has been on identifying phenomena related to heat and temperature that is contributing to the effect of variation and to develop methods and tools to enable virtual evaluations of non-nominal assemblies, concerning these phenomena for the industrial design context. The result can be divided into two major parts. One part is focused on the effect of geometric variation in different temperatures and how to evaluate them. The other part focuses on knowledge on- and techniques for evaluating the effect of heat for non-nominal welding simulation.

Using examples from industry, it has been shown that the effect of geometric variation is dependent on temperature. Therefore, in order to minimize the effect of geometric variation, the temperature in the user phase should be considered. It has also been shown that an extension of the MIC can be used to evaluate the effect of variation on the stress of the assembly.

In Paper A, it was shown that there are conflicting criteria for achieving a robust solution on part-, assembly and functional levels. It is therefore important to be able to evaluate the robustness on several levels to enable different means for evaluating the robustness on different levels. Including thermal expansion to evaluate non-nominal properties for products is an example of this.

It was further observed that one obstacle generally encountered in variation simulation, and which needed to be addressed also in combination with temperature, was the long simulation times in contact modeling during MC-simulations.

An alternative method based on formulating the contact modeling in each MC iteration as an optimization problem was proposed. This reduced the simulation times in some industrial cases significantly.

For welding, the dependency of position error on the weld-induced distortion was corroborated. A method called the SCV-method has been developed for evaluations of the robustness of non-nominal assemblies that are welded, and were shown to give reasonable results on distortion.

6.2 Future work

The research on including temperature and heat in this thesis is far from exhausted. Here are some reflections on future work.

6.2.1 Considering temperature during geometry assurance in industry

Part of this research project has been focused on methods and tools to enable variation simulation including the effect of temperature. However, further knowledge need to be gained about how to industrially implement the results. In a variation simulation, a number of measures are considered, depending on the requirement management system. How this requirement management system should be formed to assure that the effect of temperature and heat on variation is within requirement is not known. Furthermore, more research is needed to know when during the product development phase the evaluations should be made. Here, there are two conflicting interest; to allow freedom for the designer evaluations should be made early in the product development phase. On the other hand, a more mature model makes better evaluation possible. Furthermore, one type of model maturity is needed for dimensional analyses including variation and thermal expansion, while considering stresses this maturity might have to be refined.

To investigate how residual material properties and stresses from the manufacturing process influence the effect of variation is another subject to investigate further.

6.2.2 Empirical evaluation of methods for robustness evaluations of welded assemblies

The simulation of the combination of variation and welding induced deformation is more complex, in comparison to the combination of variation and thermal expansion, and is considered less mature. The work on welding in this thesis is to be considered as early explorative work and there are a number of issues to investigate further. These issues include;

- The SCV-methods need to be evaluated experimentally. By the SCV-Method, the original method presented in Paper D, with the extensions in Papers F and G, is meant.
- The generality of the SCV-method should be explored further; the method needs to be evaluated on more geometries, using different material models, and welding types with different settings.
- The techniques presented in Paper G, using bond contact instead of a consisting mesh, need to be extended and evaluated in order to incorporate deviation in all 6 degrees of freedom.
- Different approaches for using clamping to suppress the effect of variation on welding should be further investigated. Also, how the SCV-method is applicable to clamped structures needs to be explored.

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