THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Towards improvement of geometrical quality for manual assembly parts

MIKAEL ROSENQVIST

CHALMERS

CHALMERS UNIVERSITY OF TECHNOLOGY
Division of Product Development
Department of Product and Production Development
Göteborg, Sweden 2016

Towards improvement of geometrical quality for manual assembly parts

MIKAEL ROSENQVIST

ISSN 1652-9243

Technical report no. 108

Published and Distributed by
Chalmers University of Technology
Department of Product and Production Development
Division of Product Development
SE - 412 96 Göteborg, Sweden
Telephone +46 (0)31-772 1000
URL: www.chalmers.se

Printed in Sweden by
Chalmers Reproservice
Göteborg 2016

ABSTRACT

Geometrical variation affects all mass-produced products. This variation will lead to deviations from the nominal design of the product both in terms of aesthetical and functional properties.

Geometrical variation originates either from the manufacturing of the parts or from the assembly process. In order to minimize the effect of variation robust design principles are often used.

In early product development the majority of the properties in the system solutions are fixed and to change these later in the product development will be costly. In order to verify the system solution (locating scheme and tolerances), different simulation techniques are used to predict the behavior of the product. This is done using virtual tools, for example Computer Aided Tolerancing (CAT). In order to gain confidence for such tools it is very important that the simulation results are accurate and that they capture all factors that influence the product.

In this thesis the focus has been on geometry assurance and CAT simulations for products that are manually assembled. Although many things can be automated, in the automotive industry most of the final assembly is performed by humans and nothing suggests that this will change. Since humans are quite different from robots' other factors need to be taken into consideration when designing products that are to be manually assembled.

The research presented in this thesis reports current issues and problems when performing geometry assurance, robust design and CAT simulations during product development of manual assembly products. In the thesis it is shown that the level of manual assembly complexity affects costs of poor quality, failure rate and geometrical quality.

A simulation tool, is developed that simulates the robustness of an assembly both with consideration to sensitivity to variation *and* level of manual assembly complexity. The tool is implemented in a CAT system, RD&T.

Finally, a number of existing research gaps are identified for further research.

Keywords: Interview, CAT, ergonomics, geometry system, tolerance analysis and design, robust design, design for assembly, assembly, complexity, assembly ergonomics, error, action cost, assessment, calculation model, sustainable, manual assembly, assembly complexity, quality, failure, action cost.

ACKNOWLEDGEMENTS

My deepest personal thanks go to:

My supervisor Professor Rikard Söderberg, who has supported me for 15 years and is always full of encouragement and ideas. It has been an honor to work with you. Without you this research would have been impossible.

My assistant supervisor Associate Professor Lars Lindkvist, for support with RD&T and numerous talks about problem solving.

Associate Professor Kristina Wärmefjord, for always having time to listen to and answer my questions about everything from life to statistics.

Dr. Ann-Christine Falck, for the enormous work and support she has put into our research.

Björn Lindau, for being a friend and fellow researcher who can always cheer me up.

Former and current colleagues at the Department of Product Development at Chalmers University.

Vinnova, the Swedish Agency for Strategic Research, for financial support.

Finally, I would like to thank my family, and especially my wife Nina and son Ludvig, for their loving support.

Mikael Rosenqvist

Göteborg, December 2016

APPENDED PAPERS

PAPER A

Rosenqvist, M., Falck, A. and Söderberg, R., 2012, “Geometry assurance versus assembly ergonomics- Comparative interview studies in five manufacturing companies" Proceedings of the 4th CATS, - CIRP Conference on Assembly Systems and Technologies CATS2012, may 20-22, 2012, Ann Arbor, Michigan, USA.

PAPER B

Rosenqvist, M., Falck, A. and Söderberg, R., 2012, “Robust design and geometry assurance considering assembly ergonomics”, Proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition IMECE2012, Nov. 9-15, 2012, Houston, Texas, USA.

PAPER C

Rosenqvist, M., Falck, A., Wärmefjord, K. and Söderberg, R., 2013, “Operator related causes for low correlation between cat simulations and physical results”, Proceedings of the ASME 2013 International Mechanical Engineering Congress & Exposition IMECE2013, Nov. 13-21, 2013, San Diego, California, USA.

PAPER D

Falck, A. and Rosenqvist, M., 2014, “A model for calculation of the costs of poor assembly ergonomics” (part 1) International Journal of Industrial Ergonomics: volume 44 (2014) pp. 140-147.

PAPER E

Falck, A., Örtengren, R. and Rosenqvist, M., 2014, “Assembly failures and action cost in relation to complexity level and assembly ergonomics in manual assembly” (part 2) International Journal of Industrial Ergonomics: volume 44 (2014) pp. 455-459.

PAPER F

Rosenqvist, M., Falck, A., Lindkvist, L. and Söderberg, R., 2014, “Geometrical robustness analysis considering manual assembly complexity”, Proceedings of the 5th CATS 2014 - CIRP Conference on Assembly Systems and Technologies CATS2014, Nov. 13-14, 2014, Dresden, Germany.

DISTRIBUTION OF WORK

Paper A: Rosenqvist and Falck initiated the paper, the interviews were performed by Falck with support from Rosenqvist. Rosenqvist wrote the paper, with Falck and Söderberg acting as reviewers.

Paper B: Rosenqvist and Falck initiated the paper, the interviews were performed by Rosenqvist with support from Falck. Rosenqvist wrote the paper, with Falck and Söderberg acting as reviewers.

Paper C: Rosenqvist and Falck initiated the paper, the work was performed by Rosenqvist. Wärmefjord contributed with statistical methods support. Rosenqvist wrote the paper, with Wärmefjord, Falck and Söderberg acting as reviewers.

Paper D: Falck and Rosenqvist initiated the paper, the work was performed by Falck with support from Rosenqvist. Falck wrote the paper, with Rosenqvist acting as reviewer.

Paper E: Falck and Rosenqvist initiated the paper, the work was performed by Falck with support from Örtengren and Rosenqvist. Falck wrote the paper, with Rosenqvist and Söderberg acting as reviewers.

Paper F: Rosenqvist and Lindkvist initiated the paper, the work was performed by Rosenqvist. Lindkvist contributed with programming in RD&T. Rosenqvist wrote the paper, with Lindkvist, Falck and Söderberg acting as reviewers.

TABLE OF CONTENTS

1. INTRODUCTION

This chapter describes the background of the research and introduces the basic concepts within the research area. The goal is to provide an understanding of the research questions.

1.1. BACKGROUND

Regardless of which type of manufacturing process is used to create a product it is afflicted by variation. The variation will affect the final product both aesthetically? and functionally. In some cases, this leads to that the requirements for the product are not fulfilled, resulting in additional costs and underperforming products. It is not possible to avoid variation but several methods to decrease variation and decrease the effect of variation are available and used in product development today. In this thesis variation that comes from manual assembly, i.e. humans, is explored. (Chase, K. & Parkinson, A., 1991; Hong, Y. & Chang, T.C., 2002; Nigam, S. & Turner, J., 1995) The work has mostly been conducted in the context of the automotive industry but the results are applicable to other types of industries.

Variation that effects the final product consists of two main contributors; part variation from the manufacturing process and process variation from the assembly process. Part variation could be variation in form and size, process variation could be fixturing errors, variation in equipment used etc. The focus in my research is within process variation for manual assembly products.

The management of variation, often called tolerance management, is a crucial part of the product development process and needs to be in focus during all phases of product development and production. In order to maximize the profit for a product it is necessary to use tolerances that are optimal for the design intent. Too tight tolerances will increase costs and too large will result in a poor product. Therefore, it is very important to be able to predict variation and its consequences in all phases of the product development. (Söderberg, R., Lindkvist, L. & Carlson, J., 2006)

Tolerance management has different focus in different phases of product development. Simplified a product development and product can be divided into 3 main phases, seen in Figure 1.

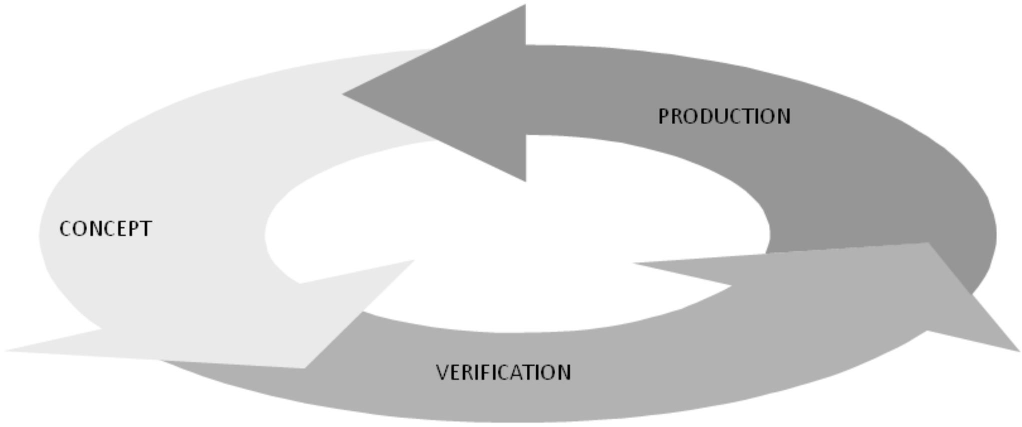

FIGURE 1: THE PRODUCT REALIZATION LOOP

Concept Phase:

Product concepts are generated and evaluated. One or several concepts are selected for further work. The focus in this phase is Robust Design, i.e. minimize the effect of variation. Variation simulation and tolerance analysis is done to optimize the system solution, i.e. locating scheme and sizes of tolerances. Verification is done virtually.

Verification Phase:

In this phase the Product design is finished and the task is to test and verify the product performance and the process. The focus in this phase is to verify that all geometrical requirements are fulfilled - not only virtually but physically.

Production Phase:

In this phase the focus is to manage the product and process according to what was developed during the concept and verification phase and to maintain a stable process that fulfills all geometrical requirements.

The research carried out in this thesis is a part of the research conducted by the research group for “Geometry Assurance and Robust Design” at the Wingquist Laboratory at Chalmers University of Technology in Gothenburg, Sweden. This research group deals with methods for minimizing the effect of geometrical variation in assembled products, and there are research activities in all phases of the product realization cycle. The Wingquist Laboratory is an internationally competitive competence center for multi-disciplinary research within the field of efficient product realization.

1.2. GEOMETRY ASSURANCE AND ROBUST DESIGN

A collection name for all activities that aim to reduce geometrical variation on the final product is Geometry Assurance. The goal of this is to improve the ability to meet and exceed customer expectations and to reduce costs at the same time. This aligns well with the definition of improvements in product development (Ullman, D. G., 2003)

The most important work within geometry assurance is done during the concept phase. In the early product development, it is crucial to find a good concept, a concept that has high geometrical robustness, i.e. insensitive to variation. This means that a robust concept suppresses the incoming variation. The robustness is determined by many factors such as shape, split lines and assembly process, but the most influencing factor is the locating schemes (Söderberg, R. & Lindkvist, L., 1999). It is possible to optimize the locating schemes with respect to robustness (Lööf et al., 2009) however in reality other factors influence robustness and the choice of locating schemes. A set of tools supporting the geometry assurance process is presented in Söderberg et al., 2016.

1.3. Locating Schemes

The purpose of a locating scheme or positioning system is to fixate a part in a desired position in space. For rigid parts that means six degrees of freedom; three translations and three rotations. To achieve this 6 points are needed to locate it into space in 3 linearly independent directions. These six points are called locators and can be realized on the part by pins, holes, slots, surfaces etc.

The fundamental type of positioning system for rigid parts is the 3-2-1 locating scheme, see Figure 2. The primary points A1, A2 and A3 define a plane and lock the geometry in space in two rotations (RX and RY) and one translation (TZ). The secondary points, B1 and B2, define a line and lock the geometry in space in one rotation (RZ) and one translation (TY). The tertiary point C1 locks the geometry in space in one translation (TX). (Söderberg, R. & Lindkvist, L., 1999)

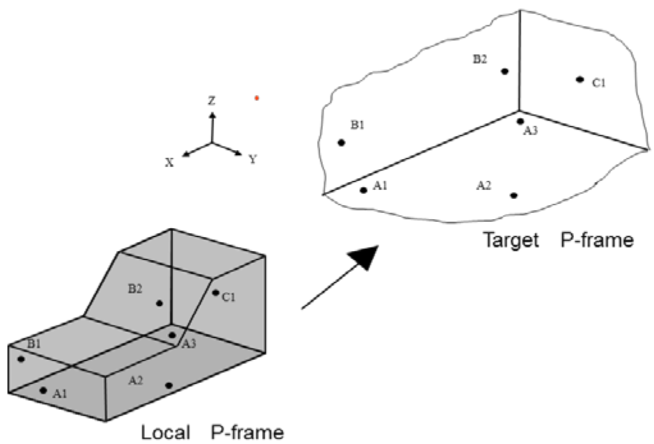

FIGURE 2: THE 3-2-1 LOCATING SCHEME

The physical realization of the locating schemes can be done in different ways for different types of parts and processes. My research has focused on manual assembly parts where no aids, such as fixtures are used, instead the locating scheme is built into the design of the parts and it is up to the operator that assembles the part to ensure that all degrees of freedom are locked.

1.4. MANUAL ASSEMBLY

The assembly systems of today are very complex due to focus on mass-customization products (Coletti, P. and Aichner, T., 2011) that should be manufactured in a production flow for mass-production. Further the number of variants is steadily increasing (Hu et al., 2008) to satisfy customer demands. In the automotive industry the number of different types of vehicles is steadily increasing along with the number of options that the customer can specify all to be assembled on the same paced line (Zhu et al., 2008). This puts high demand on the assembly process to cope with high flexibility and a high number of variants while keeping the production costs down.

Because of this final assembly work is often carried out manually by a human that has the capacity to be flexible and versatile. (Fasth et al., 2010). It is not feasible to have automated assembly in a mass-customization production line; the cost supersedes the gain. In an automotive paced line, it is typical that a number of different vehicle are manufactured simultaneously with thousands of customized combinations. This puts enormous pressure on the operation of the assembly systems. (Rekiek et al. 2000) In these environments the human operator is the best choice for assembly, however the product must be designed for manual assembly to avoid assembly errors. In designing the production system, it is important to keep physical (Falck et al., 2010) and cognitive load levels (ElMaraghy and Urbanic, 2004) on the operator as low as possible, something that is often in conflict with the aim of the employer to maximize the throughput of the paced line. Two examples from the automotive industry of high load levels can be seen in Figure 3.

FIGURE 3: MANUAL ASSEMBLY OPERATIONS WITH HIGH LOAD LEVELS (VOLVO CAR GROUP)

When the operator assembles a part, the error to that parts position that is related to the assembly operation is called operator variation or process tolerance. This is one contributor to variation. In order to be able to correctly predict the geometrical quality it is very important to have knowledge of all contributors to variation and today there is limited knowledge about operator tolerances.

1.5. COMPLEXITY AND COSTS OF POOR QUALITY

The ease of assembly has previously been defined as the ease of gripping, positioning and inserting different parts into the assembly process (Fujimoto and Ahmed, 2001) an expansion of this is to talk about operator choice complexity. Operators need to make many choices under time pressure, for example carrying out operations in the correct order, picking the correct fastener, using the correct tool etc. The term complexity can be defined as something that is difficult to understand, describe, predict or control (Sivadasan, S., et al 2006).

This puts very high demands on the operator's performance, both physical and cognitive, which results in assembly errors being made by the operator. These errors result in different quality issues that create costs of poor quality. Previous research has shown that costs of poor quality can be 10-40% of a company turnover. (Harrington (1987), Bank (1992) and Booker et al. (2001). It is therefore desirable to find methods to minimize the complexity for the operator and thereby reduce the costs of poor quality.

1.6. VARIATION SIMULATION

Variation simulation is used to predict variation and offset (deviation from nominal design) in critical dimensions. This is to verify that the geometrical requirements set on the product are fulfilled. Variation simulation is mainly used as a virtual verification method during the concept phase of the product development.

Two main inputs are used for variation simulation; locating schemes that dictate how variation propagates in the assembly and tolerances that describe which variation can be expected.

A variation simulation consists of first identifying all factors contributing to variation and then including them into a simulation model. If the results of the variation simulation are to be accurate it is necessary, that the virtual simulation model built is replicating reality correctly and containing all contributors to variation. When this is fulfilled the simulation can replace physical tests and prototype builds. This leads to lower costs, scrap and shorter lead times.

1.7. RESEARCH GAP AND RESEARCH QUESTIONS

The contributors to variation for manual assembly parts are different from parts that are assembled automatically. The design of the parts and processes needs to be done with somewhat different requirements than from, for example, parts assembled by a robot. Traditional methods and tools for geometry assurance can therefore be inadequate in replicating the assembly process and capturing the contribution from the operators. The overall goal of this research is to generate new knowledge, tools and methods for proactive geometry assurance of manually assembled parts thus improving the geometrical quality of the final product.

By studying geometrical quality for parts that are manually assembled both in virtual context (requirements, simulations, tools, organizations etc.) and physical context (observations, measurements, interviews etc.) new knowledge is collected. This knowledge is used to develop new tools and methods to improve robustness, and thereby geometrical quality, for manually assembled parts.

With this aim the research conducted can mainly be grouped under four general research questions:

Main research topic: How can geometrical quality for manual assembly be improved?

Research Question 1:
How does manual assembly affect product quality and ergonomics?

Research in product development requires an understanding of the situation and its problems. In this question issues regarding manual assembly in relation to quality are elaborated on and put in relation to existing literature.

Research Question 2:
How can assembly complexity be considered in early development phases?

The focus for this question is to investigate how to include assembly complexity when the product concepts are generated. Both with respect to tools and methods and with respect to organization, roles and responsibility.

Research Question 3:
How can manual assembly factors be considered in CAT?

When performing virtual geometry assurance in early phases most of the work is done in Computer Aided Tolerancing (CAT) tools. The main task is to maximize the geometrical robustness of the product concepts. This question aims at understanding how robustness of manual assembly concepts can be simulated.

Research Question 4:
How can operator variation be included in CAT?

During the latter part of the concept phase in product development the focus shifts from creating robust concepts to prediction of variation. The accuracy of the prediction is dependent on all contributors to variation being included in the simulation model. This question deals with how variation originating from the operator can be included and predicted.

1.8. DELIMITATIONS

The focus of this research has been to find means to improve geometrical quality for manually assembled parts with emphasis on the operator. There are other factors that can be researched that also influence geometrical quality, these have not been addressed.

There are other ways to assess manual assembly complexity than the method used in this research but these have not been elaborated.

The assumption is made in CAT simulations that all parts are rigid bodies.

1.9. OUTLINE OF THE THESIS

The work that makes up this thesis has been performed within two different research projects:

1. Hållbara produktionsstrategier: ”Beslutsstöd för tidig estimering av kvalitetsbristkostnader” Vinnova 2009-03954 Hållbara produktionsstrategier.
2. Hållbar produktionsteknik: ”Proaktiv monteringsergonomisk och geometrisk kvalitetssäkring för hållbar produktion” Vinnova 2013-02416 FFI Hållbar produktionsteknik.

The first project mainly addressed answering research questions 1 and 2 and the second project answering research questions 3 and 4.

The structure of the thesis is as follows:

- **Chapter 1:** Introduction to the topic is given and the research gap and questions are introduced.
- **Chapter 2:** Frame of reference aiming to give an overview of previous work and knowledge within the research area.
- **Chapter 3:** Research approach and methodologies used
- **Chapter 4:** The results are summarized.
- **Chapter 5:** The results and their quality are discussed.
- **Chapter 6:** Conclusions and future work.

2. Frame of Reference

In this chapter, an overview of previous work and knowledge within the research area in question is given.

2.1. Geometry Assurance

The outline and content of this chapter follow roughly the product development process, shown in Figure 4 with emphasis on geometry assurance.

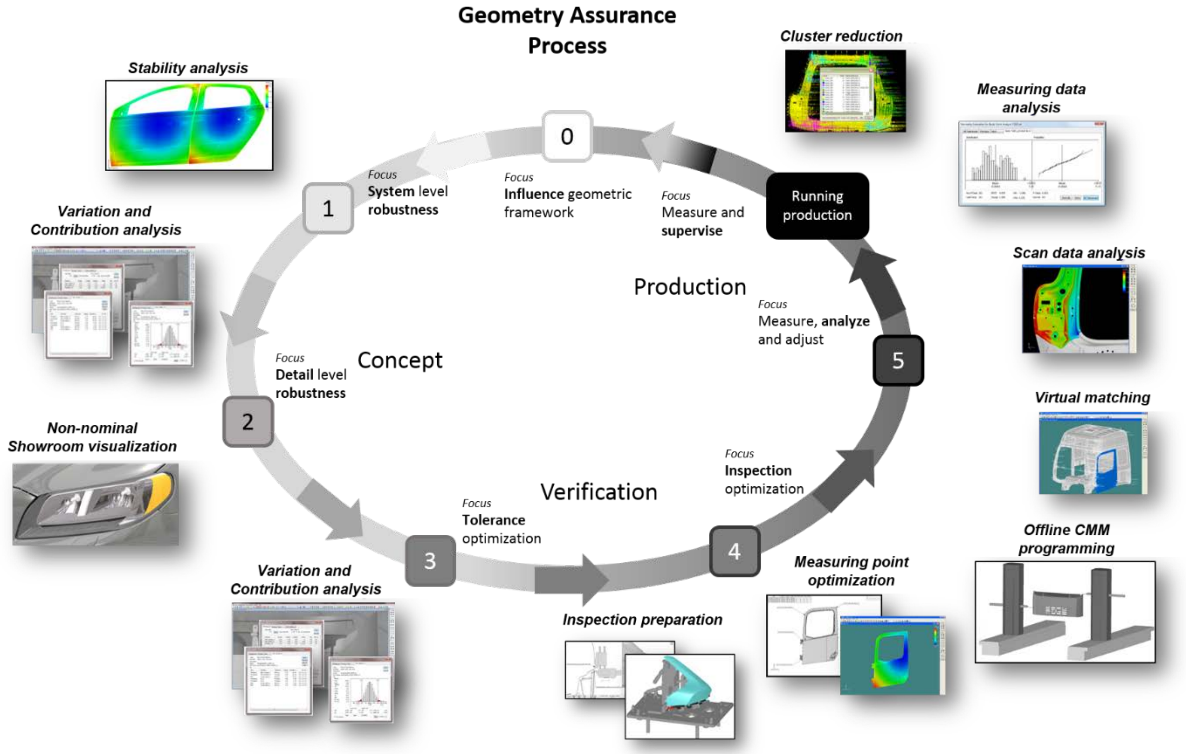

FIGURE 4: THE OUTLINE OF THE FRAME OF REFERENCE IN RELATION TO THE PRODUCT DEVELOPMENT PROCESS

A product development process consists of three main phases, concept, verification and production. A geometry assurance process is a sub-part of the product development process that describes the development activities that are connected to geometry assurance.

During the Concept phase many product concepts are generated and evaluated. In the beginning of this phase the focus is set on **Robust Design** which is evaluated and optimized by creating **Locating Schemes** and performing Stability analysis. Later in this phase the focus is on balancing and assigning **Tolerances** which are evaluated and optimized using Non-nominal visualization and variation and contribution analysis. To use this analysis, knowledge of a number of statistical terms and concepts is needed so a short summary of some **Basic Statistics** is included in this chapter. Products contain lots of different parts and assembly concepts, in this thesis the focus is on **Manual Assembly** parts, a very important factor for manual assembly parts is the level of **Complexity** for the assembly task which has been investigated in several of the publications together with the **Costs of Poor quality** that the assembly process can induce. Therefore, overviews of these topics are included.

In the verification phase the product is slowly being produced, at first with non- production intent process and tools and later with the intended process and tools ramping up the production pace. The focus in this phase is to physically verify that all geometrical requirements are fulfilled and if it is necessary to perform activities to correct any problems.

During production the main task is to measure and supervise the production so that the geometrical requirements are fulfilled over time. Production knowledge and inspection data are also fed back to the next concept phase as in-data for new product development.

Finally, there is also a short discussion about **Quality of simulation** in the frame of references, since this is always important to consider when developing computer aided design tools.

2.2. Robust Design

A Robust Design is a design that fulfills its requirements even when noise, in this case variation, is present. Usually it is difficult or expensive to reduce the size of the sources of variation, instead the goal is to reduce the sensitivity to variation (Taguchi et al., 2005). The original idea behind robust design and quality improvement was introduced by Taguchi (1986) and has been refined and expanded since then. The main idea is to determine which factors affect a concept and divide them into control factors; those that can easily be controlled, and noise factors (variation); those that are difficult to control. To achieve a robust design, the control factors are chosen so that the expected loss caused by the noise factors is minimized. When these principles are applied to geometry assurance, control factors are the locating schemes and noise factors are the variation (Söderberg, 1998); (Söderberg & Lindkvist, 1999).

To optimize the locating schemes for robustness the task is to find the best position of the locators in regards to the geometrical shape of the part so that the sensitivity to variation is minimized. This can be done using a CAT-tool and Stability analysis (Söderberg & Lindkvist, 1999). Using the stability analysis, the engineer can compare several product concepts and find the most robust solution iteratively. Other approaches to optimization of robustness for geometry assurance can, for example, be to only evaluate the sensitivity to variation in critical measures (Lööf et al., 2009).

2.3. Locating Schemes

Locating schemes are a crucial concept in geometry assurance. The locating scheme is the definition of how a part is positioned in space, by a fixture and/or other parts. The locating scheme is used for manufacturing, assembly and inspection to ensure that the part is correctly positioned. A rigid body part has six degrees of freedom, three translations (TX, TY, TZ) and three rotations (RX, RY, RZ) and therefore needs six points to lock all translations and rotations in three independent directions. In reality it is common that some points coincide, but at least 3 locators are necessary. The locating points are commonly realized physically with pins in holes or slots and different types of surfaces that are clamped.

It is very important that the positioning of parts is stable and error free. If variation of the positioning is introduced during assembly, the quality and function of the finished product will be affected. As mentioned, previously, stable positioning is ensured by creating a locating scheme with high robustness. How much variation is introduced in the assembly is related to the operator’s ability to position the part as intended by the locating scheme.

There are two main types of locating schemes, orthogonal and non-orthogonal. For orthogonal types the three independent directions are orthogonal to each other. Several variants of positioning systems are available (Söderberg et al., 2006).

- 3-2-1 locating scheme, orthogonal:

  A1, A2 and A3 define the primary locating plane and lock TZ, RX and RY. The secondary locating plane is defined by the points B1 and B2, locking TX and RZ, while the last point, C, defines the tertiary locating plane and locks TY. All planes are perpendicular to each other. In the automotive industry this type of positioning system is seldom used since the parts have too complex shape. See Figure 5.

- 6-directions locating scheme, non-orthogonal:

  The points D1-D6 all have unique locating directions (as long as it is not singular) that are non-orthogonal to each other. In reality this is the type of positioning system that is used in the automotive industry since the parts usually have very irregular shape. See Figure 5.

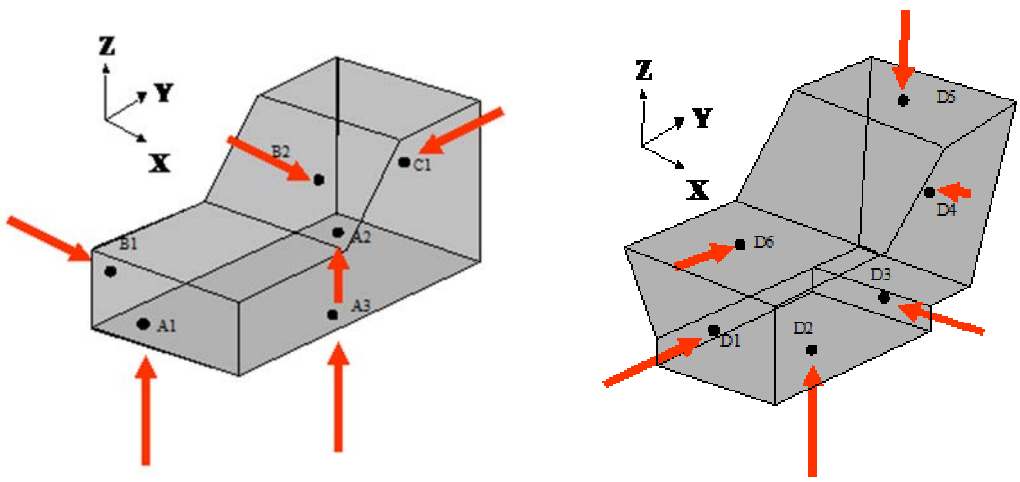

FIGURE 5: LEFT PART: 3-2-1 LOCATING SCHEME AND RIGHT PART: 6-DIRECTIONS LOCATING SCHEME (SÖDERBERG ET AL., 2006)

2.4. BASIC STATISTICS

When using CAT-tools for geometry assurance several statistical principals and terms are used, because of this a short summary of some of the statistical terms that have been used in this research will be given here.

The idea behind statistics is to analyze data sets and make inferences about the data sets when the sample size of the data set is limited. The probability density function, $f(x)$, states the probability density of a random variable X at x. For geometry assurance in the automotive industry the most used statistical distribution is the normal distribution and it has been shown that this is a reasonable assumption (Jami et al 2007). It is characterized by a mean value μ that is the center of the distribution and the variation σ that is the spread around the mean value (Rice 2006). See Figure 6.

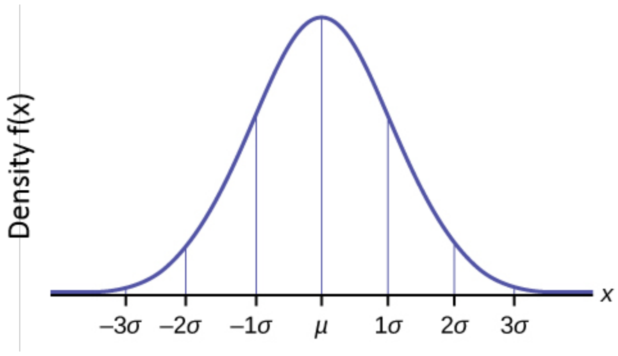

FIGURE 6: PROBABILITY DENISTY FOR A NORMAL DISTRIBUTION

A few basic statistical terms are stated in Table 1 (for variable X, original list in (Wärmefjord, 2011)), see next page.

TABLE 1: SOME STATISTICAL TERMS

Notation	Formula	Additional info
Expected value	$\mu = E[X] = \int_{-\infty}^{\infty} xf(x)dx$	Mean value for population
Mean value	$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$	Approximated mean value from a data set
Variance	$\sigma^2 = E[(X-\mu)^2] = E[X^2] - E[X]^2$	How far a set of numbers are spread out
Standard deviation	$\sigma = \sqrt{\sigma^2}$	Dispersion of a set of data values
Sample variance	$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2$	Approximated variance from a data set
Capability index	$C_p = \frac{USL - LSL}{6\sigma}$	Statistical measure of process capability, the ability of a process to produce output within specification limits. Only for normal distribution.
Adjusted capability index	$C_{pk} = \min\{\frac{USL-\mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\}$	This index takes the mean value (mean shift) into consideration.
Normal density function	$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$	A function that describes the relative likelihood for this random variable to take on a given value
Distribution function	$P\{a < X < b\} = F(b) - F(a) = \int_a^b f(x)dx$	Found in statistical tables.

2.5. TOLERANCES

All products are affected by variation, both from the manufacturing processes, i.e. stamping, cutting, milling etc., and the assembly process, i.e. equipment variation, robot variation, operator variation etc. It is very important to consider and quantify the allowed variation in each property in early product development (Ullman, 2003). This is done by specifying tolerances for each property, that describe the upper and lower specification limit, for which the property is acceptable.

Together with the positioning systems, tolerances are the most important factor that affect the final variation of a product (Söderberg et al, 2006). Defining tight tolerances is one way of achieving a good geometrical quality but costs a lot of money. It is preferred to design solutions that are robust, i.e. insensitive to variation, which allows larger tolerances without affecting the geometrical quality.

Two types of tolerancing types occur:

- Traditional dimensions tolerances where a lower and upper limit is set on a dimension, see Figure 7.

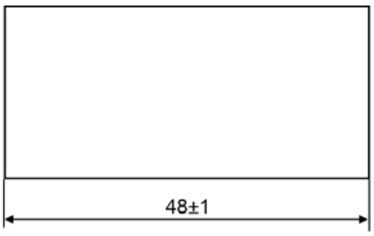

FIGURE 7: DIMENSION TOLERANCE

- Geometrical tolerances that limit a feature in 3D, form, orientation, location and runout, see Figure 8.

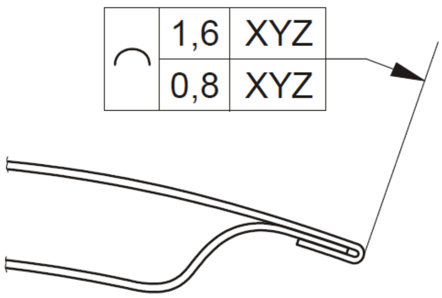

FIGURE 8: GEOMETRICAL TOLERANCE

The topic of tolerances has been extensively researched, a good example is (Hong and Chang 2002).

When setting tolerances, and balancing them, two strategies can be used.

Bottom-up: Tolerances are allocated from single part level, based on previous knowledge of similar parts or manufacturing processes and the tolerance and the final product is a result obtained by adding all the underlying tolerances (Hong & Chang, 2003).

Top-down: A tolerance specification is set on the final product to start with. This is then broken down into individual tolerances on the included parts that are balanced to meet the specification of the final product (Lööf 2010). In the automotive industry this method is the most commonly used. In both strategies it is very important to be able to simulate and predict the final geometrical outcome using 3D tolerance chain calculations tools, CAT-tools.

2.6. VARIATION SIMULATION

In section 2.5 it is described that it is necessary to have a tool that can predict variation in the final product. In this thesis the CAT-tool RD&T has been used to predict variation, and some of the analysis methods in this will be descried in this section. However, firstly an introduction to different methods to simulate variation will be complied.

2.6.1. METHODS FOR VARIATION SIMULATION

Many different ways are available for predicting how variation propagates throughout a product, some overviews of this can be found here (Chase & Parkingson 1991; Nigam & Turner 1995; Gao et al 1998; Hong & Chang 2002).

Two main types of techniques are generally used to predict variation, deterministic and Monte Carlo simulation based methods.

- Deterministic: Normally based on Taylor expansions of the function that relates input variation X_i (tolerances on parts, equipment and process) to output variation $f(X_1, X_2, \dots, X_n)$ (measures of critical geometrical properties on the final product). f can then be approximated:

$$f(X_1, X_2, \dots, X_n) \approx f(\mu_1, \mu_2, \dots, \mu_n) + \sum_{i=1}^{n} a_i (X_i - \mu_i), \qquad [1]$$

  $a_i = \frac{\partial f}{\partial X_i}(\mu_i)$ describes the sensitivity of the assembly, and the input tolerances X_i are presumed to have a certain distribution with an expected value μ_i and variance σ_i^2. The tolerances of X_i are $\pm t_i$ and the final accumulated tolerance of the assembly is T.
- Worst case tolerance analysis: In this prediction all tolerances are presumed to be at their tolerance limit, worst allowed value, at the same time. This means that, given that all components are within tolerance limits, all produced products will fulfill their geometrical requirements. In reality it is very unlikely that all tolerances will be at their limit and this method will result in an over-pessimistic prediction (Nigam & Turner 1995).
- Statistical tolerance analysis: In this prediction the tolerances are presumed to be connected to a stochastical distribution that describes the outcome. This assumes that they are distributed close to their mean values following a normal distribution. The RSS (Root Sum Square) method is shown in equation 2:

$$T = \sqrt{\sum_{i=1}^{n} \left(a_i t_i\right)^2}$$

This method will give an overly optimistic prediction (Nigam & Turner 1995) and can therefore be adjusted up using a scale factor and/or mean drift compensation. This method was previously used in the automotive industry for prediction of variation before CAT-tools were used and can still be used for simple products today.

The pros of deterministic methods are that they are low on computational use but the cons are that the accuracy can be questioned (Cai et al, 2006).

- Monte Carlo simulation: Based on the principle to generate a large number of samples for each input tolerance with a random number generator for a selected distribution. The samples are then used iteratively in the function that describes how variation propagates in the assembly to predict the variation in the final product. In order to have reliable results from Monte Carlo Simulations a large number of samples is required which results in this method being computational time demanding. However, the accuracy of the method is good (Nigam & Turner 1995). This method is commonly used in commercial CAT-tools and is the usual method used in the automotive industry.

2.6.2. DIFFERENT KINDS OF ANALYSES IN RD&T

Many commercial softwares (CAT-tools) for geometry assurance that include variation simulation are available. Some large brands are 3DCS, VisVSA and RD&T. In this thesis RD&T has been used for simulations and research. Variation simulation in RD&T is based on the Monte Carlo simulation method described in section 2.6.1. To illustrate typical types of analysis in CAT-tools RD&T will be used in the following section. RD&T is used in a number of automotive companies, such as Volvo Car Group, CEVT, Volvo Trucks, Scania, Ford, JLR etc.

Working procedure for geometry assurance is described in section 2.1. The first task is to optimize the robustness of the assembly using the stability analysis.

- Stability analysis: Evaluates the geometrical robustness of the locating scheme. A unit disturbance is applied to all locators one at a time. The quota between input disturbance and the output deviation in all points of the geometry is calculated and the sensitivity to variation is found. For each point on the geometry this is then Root Sum Squared for each point to find the total sensitivity (Söderberg, 1998) and (Söderberg & Lindkvist, 1999). The result is usually presented as color-coding of the geometry where blue is low sensitivity (robust) and red is high sensitivity (un-robust), see Figure 9. The locating scheme is optimized so that the important areas of the geometry are as blue as possible.

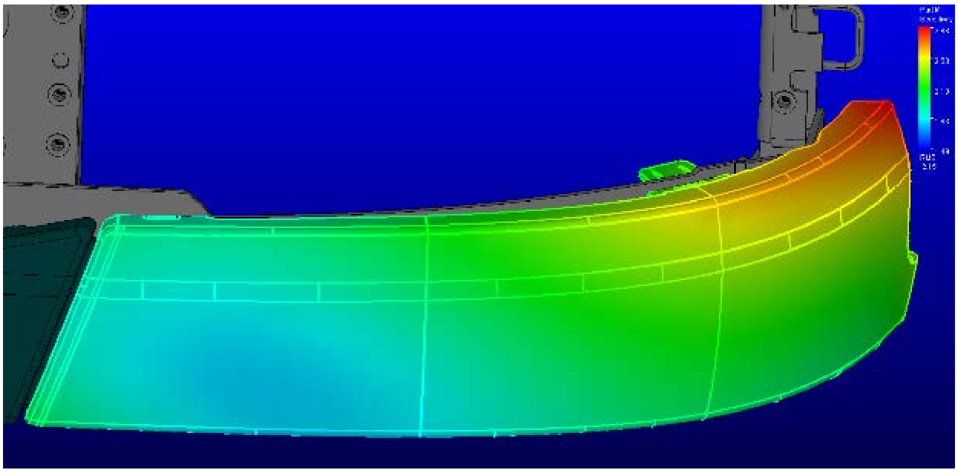

FIGURE 9: STABILITY ANALYSIS IN RD&T

The next step in geometry assurance, as described in section 2.1, is to assign and balance tolerances for all features of the assembly. In order to do this, it is necessary to be able to predict variation and to find out the relative importance of each tolerance. This is done using variation analysis and contribution analysis.

- Variation analysis: Statistical variation simulation based on the Monte Carlo-method is used to apply a number of input disturbances (tolerances) to the assembly. These are usually normally distributed. The result is a prediction of variation in the final assembly. Common used output formats are 6 sigma or 8 sigma as measures of variation. The result is presented both in numbers and in a histogram, see Figure 10.

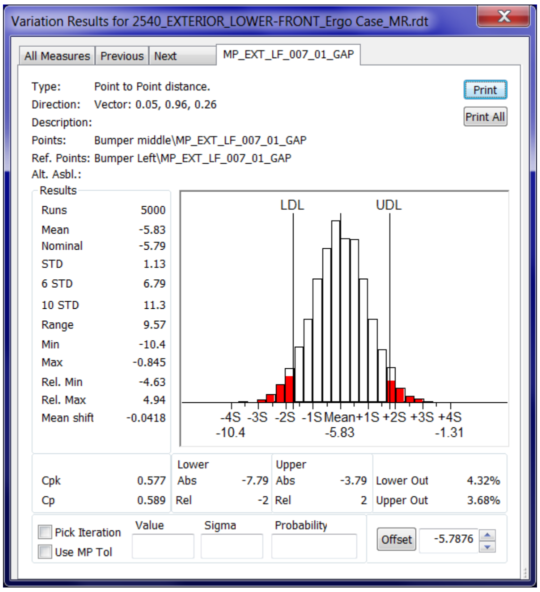

FIGURE 10: VARIATION SIMULATION IN RD&T

The measure on the final assembly in Figure 9 is not within its tolerance limits and therefore the design needs to be changed. In order to do this, it is necessary to analyze the impact of each tolerance on the final assembly, this is done with contribution analysis.

- Contribution Analysis: Calculates the relative importance of each input deviation (tolerance) on the output deviation. The result is presented as a ranked list with the contribution of each tolerance on the variation simulation. The contribution analysis is done by varying the influencing parameters, one at a time, at three levels HLM (high, low, mean) and registering the result. See Figure 11 for a typical result. Using this list the most important tolerances can be identified and possibly be reduced to improve the result on the final assembly.

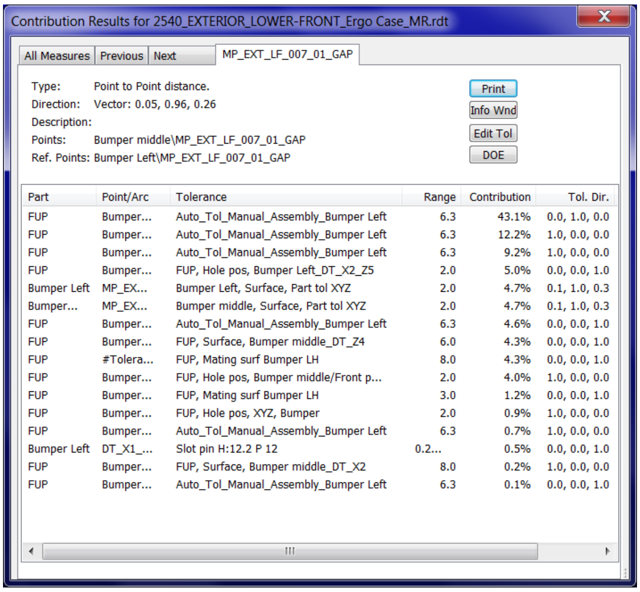

FIGURE 11: CONTRIBUTION ANALYSIS IN RD&T

2.7. MANUAL ASSEMBLY

Challenges in the global market has forced manufacturers to increase their product variety and diversify their products, often denoted mass-customization, the aim is to produce products that are customized to a cost that is close to the cost of producing mass-produced products (Zhu et al, 2008). The effect of this is that the production and production layout must be very flexible and this puts very high demands on the equipment that performs the assembly.

In the automotive industry the early stage of assembling a vehicle, assembling the sheet metal body, shows a very high level of automation, humans often just supervise and repair the equipment. The process of assembling the body is fairly constant, has few variants and is not changed a lot during the product lifecycle, ideal for high level of automation and investments in expensive equipment. This gives high level of manufacturing robustness, high repeatability and process tolerances that are easily measurable. It also gives an inflexible product line and long lead times for changes.

In the later stages of assembly, often called final assembly, most companies have had to abandon previous strategies of full assembly automation due to the markets' demand of mass-customization, high costs of automation and the (at least) yearly revisions and changes of the products. It is simply not feasible to have automated assembly in a paced line that has evolved so far from the original mass-production principles. However, this presents a problem, a common solution to create sustainable production solutions is to introduce machines that do the work that is not suited for humans but now the assembly operations need to be adopted for humans. (Fasth and Stahre, 2008, Endsly, 1997)

Due to the reasons stated above the final assembly in the automotive industry is often carried out manually by human operators with low level of automation (Fasth et al., 2010). Human operators have many advantages; flexibility, creativity, ability to interpret a broad variety of information, adapts to the environment (solve problems) etc. (Billings 1997). In addition, the shift toward Lean Production introduces the concept of continuous improvements, kaizen, which is an element that requires human operators to work successfully (Shah and Ward, 2007).

Together with this, increasing demands for social sustainability at the workplace is affecting the assembly processes. Today it is not accepted to wear out workers and replace them when they do not perform. It is also important to have a workplace that can handle all types of ages, genders, health status etc.

All these factors need to be considered when the product is designed, and even more commonly, when the process is designed. The work presented in this thesis aims at presenting a method for this.

2.8. Design For Assembly (DFA) and Design For Manufacturing (DFM)

A commonly used framework to simplify assembly and manufacturing operations is to use the principles of Design For Assembly (DFA) and/or Design For Manufacturing (DFM). The first systematic methods of the principles were the Boothroyd Dewhurst design for assembly method (Boothroyd and Dewhurst, 1983). The idea behind the methods is to evaluate every part as it is assembled to the product to measure the difficulty of each step in the assembly process. The individual measurement values are then summed up to achieve a score of the assembly difficulty for the product, the aim is to reach as low score as possible.

The original DFA/DFM methods have been developed over the years into several DFA/DFM that differ slightly from each other (Warnecke et al., 1988, Miles et al., 1992), many large companies have made their own interpretation of the principles as well, such as Ford and Texas Instruments.

Often both DFA and DMA are used in conjunction and then labeled DFMA, constituting a framework and method for analyzing a design both from the point of assembly and manufacturing (Boothroyd et al., 2002).

These methods focus on reducing the number of parts to assemble, improvement of grasping the parts and the overall handling of the parts. The methods are used both in the concept phase and verification phase as support to the design engineers, very similar to the methods developed in this thesis. Although the methods have proven to improve quality (Boothroyd 1994) it is not enough to gain high quality and low failure rates in a combination of mass-production and mass-customization. In the context of the automotive industry today additional focus is needed to handle the increasing physical and cognitive loads that the operator is subjected to.

In DFA/DFM the aim is set to simply the product and increasing assembly speed, not evaluating the design from how complex the operator perceives it to be. Therefore additional methods are needed for quality assurance today.

2.9. Complexity and Quality

Generally, complexity is a term that states that something is difficult to understand, interpret or control (Sivadasan, 2006). In this thesis the term has been used to assess how difficult it is for a human operator to perform an assembly operation as intended.

Several researchers have defined the term complexity in manual assembly and many different methods to assess complexity exist. However most of them have focused on how complexity relates to manufacturing system design and very few on the connection to quality of the product and failure rate. The approach to complexity in this thesis aims at connecting complexity with geometrical quality.

One approach is to evaluate the conditions in the production process (with a questionnaire) that the operator must manage. The aim is to find out how operators perceive assembly complexity at station level in the production. This can then be used to measure assembly complexity and suggest changes to the station to manage the level of complexity (Mattsson et al. 2012; 2014).

Another approach is a two-step method for assessing the assembly complexity that can be used both before and after the system solutions have been finalized. Used before it consists of a dependency matrix and a mapping regression model and after, an inherent structural systems complexity model (Samy and ElMaraghy, 2012).

The complexity of an assembly operation affects the quality of the final product (Falck and Rosenqvist, 2012; Fässberg et al., 2011). Further there is a relationship between the number of variables that the operators have to manage in an assembly task (Richardson et al, 2006) and how difficult the assembly is perceived. It has also been shown that the more options the operator has during an assembly operation the more errors will be induced by the operator (Zhu el al., 2008). One of the biggest challenges in the manufacturing industry is becoming to manage the increased complexity (ElMaraghy et al., 2012).

The costs of poor quality in a company can be as high as 10-40% of the company turnover (Harrington, 1987, Bank, 1992, Booker et al. 2001) and it has been shown that different types of assembly problems highly contribute to quality costs (Falck et al, 2010). In addition to this a major part of the bad ergonomics problems in final assembly in the automotive industry originates from the product design, not the production line (Falck, 2007).

2.10. Quality of Simulation

When developing computer aided simulation tools it is always important to consider the quality of the simulation. The purpose of using CAT-tools is to replace or reduce the need of prototype builds, physical inspections and trial and error work in the industrialization phase of the product development. The aim is that the result from a simulation should be as close as possible to the real physical result in production.

For simulation in CAT-tool that uses the Monte Carlo method the accuracy is dependent on that as many as possible of the factors (locating schemes, part geometries, tolerances) that affect the real outcome are included in the simulation model. The distribution of the input tolerances also need to be correct for the best accuracy.

This work has focused on increasing simulation accuracy by including aspects and variation related to operators performing manual assembly of parts.

To assess the quality of the simulation results two methods can be used (Bracewell et al, 2001):

- Theoretical validation: compare result with a known problem
- Experimental validation: compare result with experimental result (used in this thesis)

The validity of the research was ensured by describing the studies in a logical and consistent way, *contextual validity*, replicating the results in several companies, *external validity*, and by combining qualitative and quantitative data, *internal validity* (Yin, 2009; Ihantola and Kihn, 2010).

3. RESEARCH APPROACH

In this chapter, the research methodology used in this work is presented and justified.

3.1. BACKGROUND

In the area of geometry assurance research there is no generic research model that is always used. However, the Design Research Methodology defined by Blessing is often used (Blessing et al. 1998, Blessing and Chakrabarti 2009) for research within Product and Production Development institutions. This is the methodology that has been used in this thesis.

The work in this thesis falls under the field of design science which is defined as a human activity that aims at creating services and artifacts (Hubka & Eder, 1996). Design science connects natural science, mathematics and applied fields. The interpretation here is that design science is the search for different types of knowledge and information that helps us understand the design of a product in such a way that it enables the development of tools that can improve the probability of a successful product in one or several ways. For example, an improved quality or assemblability of the product. Research has also shown that DRM is suitable for research within computer-aided design tools (Bracewell et al., 2001)

3.2. RESEARCH METHODS IN THIS THESIS, WINGQUIST AND DRM

This research has been conducted in the Wingquist Laboratory VINN Excellence Centre within the Area of Advance - Production at Chalmers University of Technology. The research process for research conducted within the Laboratory can be seen in Figure 12.

The process consists of three gears that all are interconnected.

- The first gear needs two inputs to start a research project: an industrial need is identified that can be connected to a research challenge. Only when these two exist together is the project executed. Within this gear, research questions are formed and the research is conducted using an appropriate method. In this thesis the method has been DRM.
- The second gear is started when the research has generated a method and tool that can be transformed into a demonstrator where the industry can test the result and evaluate the validity of it. The demonstrator is usually realized in a simplified way in computer-aided design tool among the collaborating partners in Wingquist. In this thesis the tool is RD&T.
- The third gear is the implementation phase, this is done in the industry, not in the academia. The strategy within Wingquist is that research results should be implemented and used in the industry and if the industrial evaluation is satisfactory the demonstrator is developed into a commercial tool and implemented in the industry. The process has

been developed over some time and secures knowledge transfer between the academia and the industry.

The research in this thesis was initiated by an industrial need and a research gap, and is based on the Wingquist process. The research questions have therefore been chosen in such a way that they answer both an industrial need and a research challenge. The aim for the research is that it should be possible to implement it as a demonstrator that can be tested in the industry.

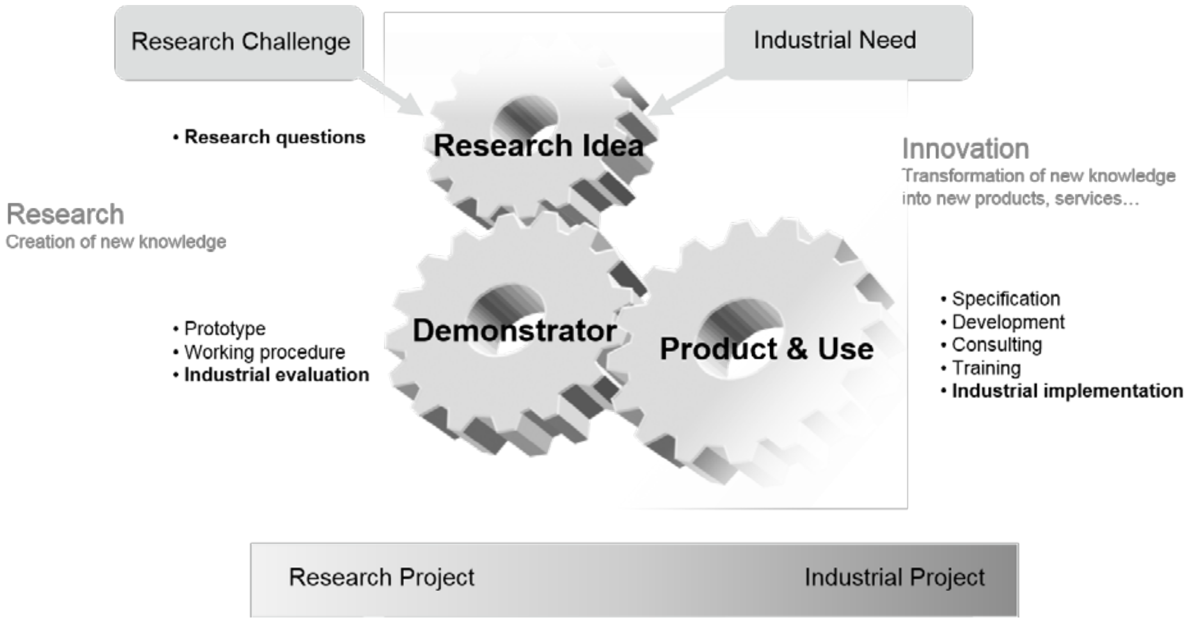

FIGURE 12: THE WINGQUIST RESEARCH PROCESS (WINGQUIST LABORATORY, 2010)

As mentioned above, the method used in this thesis is the DRM and this method consists of 4 main phases, see Figure 13.

The method is iterative and does not need to be followed in a chronological order. The amount of attention that is spent on each phase is dependent on the research topic and the amount of previous research available. Also it may not be possible to perform all phases in one research project (Blessing and Chakrabarti 2009).

Phase 1: Firstly, the Research Criteria(s) are defined, meaning that one or several measurable success criteria for the research are formulated. Example could be improved quality or accuracy. The main method in this phase is to study the situation at hand, by for example literature studies, to gain understanding of the research gap.

Phase 2: Descriptive Study I, here the existing situation, tools, procedures etc. shall be analyzed to identify the relationship to the research criteria and highlight the problems. Continued literature studies and analyses of empirical data is performed in this phase. The knowledge of the existing situation that is gained in this phase is used to identify how the research could improve the situation.

Phase 3: Prescriptive Study, the knowledge about the exiting situation from phase 2 is used to develop new improved methods, tools and procedures.

Phase 4: Descriptive Study II, in this phase the result from phase 3 is tested and evaluated against the research criteria to measure the success.

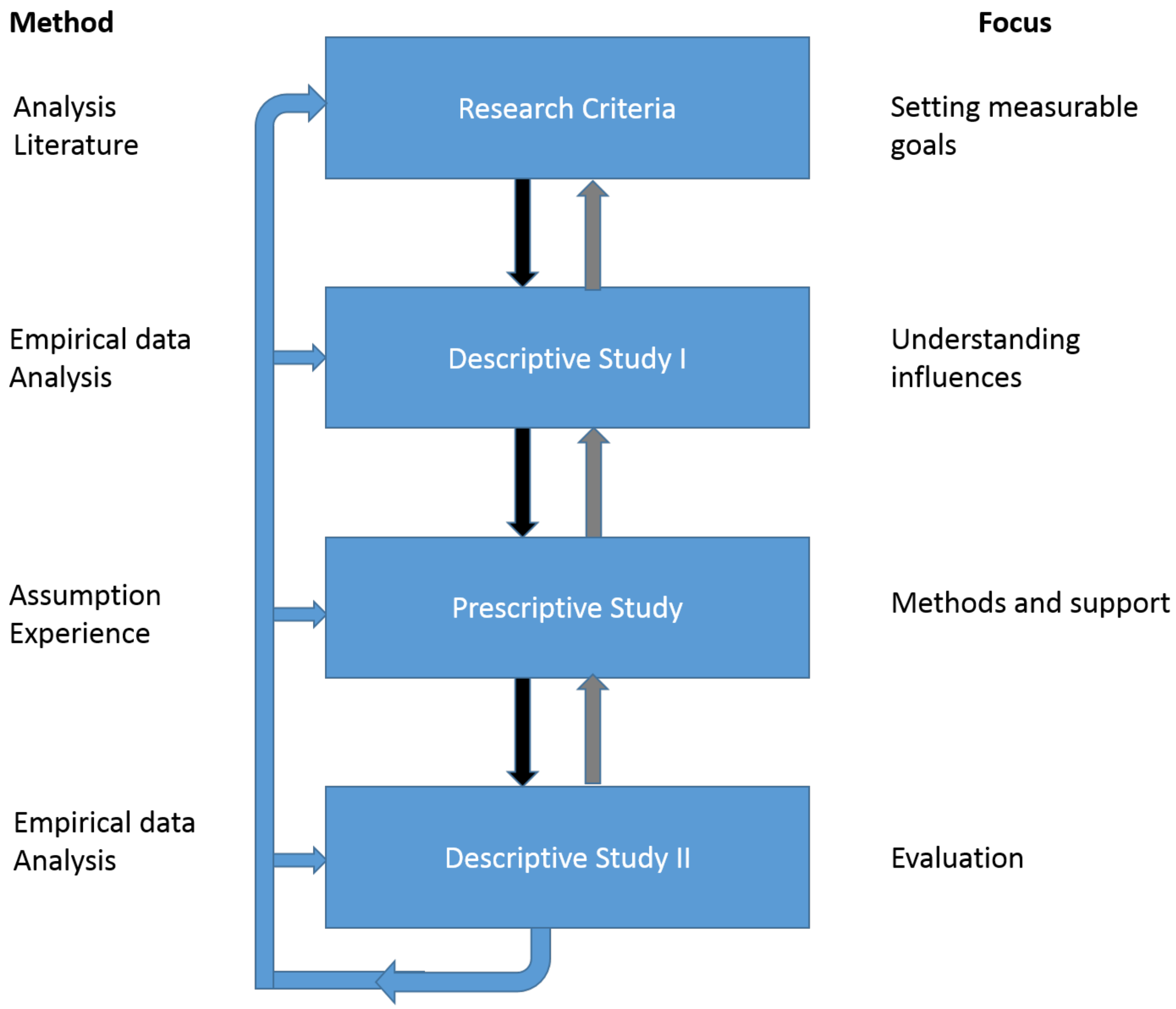

FIGURE 13: THE DESIGN RESEARCH METHODOLOGY FRAMEWORK (BLESSING ET AL., 1998)

Wingquist research process follows the DRM phases very well:

Gear one with the research idea that contains challenges both from academic and industrial views sets the research criteria that measures success. Further here the situation at hand is evaluated and elaborated corresponding to descriptive study I. Gear two that contains the demonstrator is the result of the prescription phase and the industrial evaluation is the descriptive study II. The phases are then iterated to incrementally improved the demonstrator until it is mature enough to become a part of a commercial product.

3.3. APPLIED RESEARCH APPROACH AND RESULTS

The framework for this thesis is set by the Wingquist Laboratory Research process and DRM. In this research a lot of focus has been aimed at the descriptive phase I in order to understand the problem as deeply as possible since this application of geometry assurance is quite immature.

Figure 14 shows how the research questions and papers are matched up to the DRM phases. The overall goal of this research project is to generate new knowledge, tools and methods to facilitate geometry assurance of manually assembled parts. The research criteria are: *Improved geometrical quality for manual assembly parts, including improved correlation between CAT simulations and actual production outcome and consideration of assembly factors in early geometry assurance.*

RQ1: *How does manual assembly affect product quality and ergonomics?* This research question is about understanding how manual assembly affects the quality of the product and what impact it has on the operator. The methods for answering this question were semi-structured interviews and analysis of both qualitative and quantitative data.

In paper A an interview study was conducted in Swedish industry where the focus was to investigate the general situation today regarding how geometry assurance is performed for manually assembled parts and identify possible problems. The interviews were tape recorded, transcribed and evaluated afterwards.

Paper B is a continuation of the interview study in paper A, this time with the in depth focus only on the geometry assurance and associated roles and responsibilities. This is in order to map the situation today. Several problem types were identified in this study. An embryo to a method for solution of the problems was also discussed in this study. The interviews were tape recorded, transcribed and evaluated afterwards.

In Paper D a study of quality data for over 47000 produced cars was made in order to map the cost of poor quality for manual assembly parts and the connection to how the parts are assembled. As a result of this study a method for calculating costs of poor quality was introduced.

Paper E concluded the mapping of the situation at hand, analysis of the quality data from paper D was extended to include investigation of assembly complexity and failures. The problems of current methods were shown by significant correlation between assembly ergonomics and assembly complexity, assembly time, failures and action costs. A new method to assess manual assembly complexity was applied to the results.

RQ2: *How can assembly complexity be considered in early development phases?* This research question is to understand how manual assembly complexity can be considered in early product development, instead of as more commonly today, in the industrialization phase. The methods for answering this question were semi-structured interviews, analysis of both qualitative and quantitative data and case studies.

Paper B contains an embryo to a method based on the results from paper A and B that focus on introducing the awareness of manual assembly complexity as early as possible and therefore suggest to include it in robust design.

Paper C tests the accuracy of the methods used currently, identifying several problems to the current situation including low accuracy. A solution to the problem is identified, more contributing factors need to be included in the CAT simulations.

Paper E suggests using a new method for assessing manual assembly complexity in early product development, already when the product is designed, as a method to improve quality and reduce costs of poor quality.

Paper F introduces a new type of robustness value that incorporates the method for assessing manual assembly complexity from paper E.

RQ3: *How can manual assembly factors be considered in CAT?* This research question is about how manual assembly factors can be included in the geometry assurance work that is performed in CAT tools. The methods for answering this question were semi-structured interviews, analysis of both qualitative and quantitative data and case studies.

Paper B the idea to include it into robust design is introduced and a simple CAT related function is discussed

Paper C further elaborates the idea from Paper B and emphasises the need to include additional factors into CAT simulations.

Paper F finally concludes all the research into a new interpretation of geometrical robustness including both consideration to sensitivity to variation and manual assembly complexity. The new method and robustness value is implemented in the CAT tool RD&T as a demonstrator and as a proof of concept the method is tested on a simple industrial case.

RQ4: *How can operator variation be included in CAT?* This research question is about how operator variation can be predicted in CAT tools and this question has not been addressed in this thesis but will be addressed in the PhD thesis.

For all the research questions, or parts of work in this thesis, the goals have been quite clear. This is perhaps due to the fact that all research questions are linked to industrial challenges, due to the Wingquist Laboratory research process. Since the goals are clear, the formulation of the criteria is facilitated. Clearly stated criteria also make the Description II phase, the evaluation, much easier. In a rough outline, the content of the first description phase can be divided into two main parts; an investigation of the present working procedure at the industrial partner and a literature study to review previous work within the area. This work also provides input and ideas for the prescription phase.

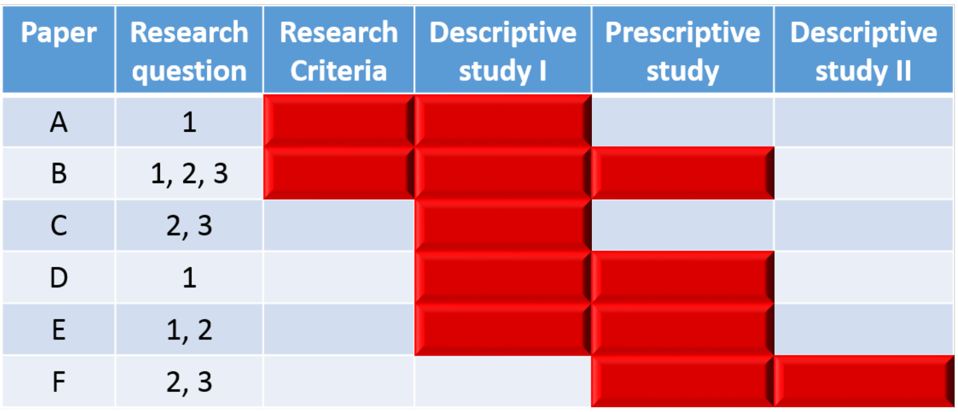

FIGURE 14: DRM APPLIED TO THE RESEARCH CONSTITUTING THIS THESIS

4. RESULTS

In this chapter, a summary of the appended papers is given, and the results are discussed.

4.1. SUMMARY OF APPENDED PAPERS

In this section short summaries of the appended papers are provided, their results and interconnections will be presented. The papers are presented in the order the research was performed. However, this order does not coincide with the order in which they were published.

4.1.1. PAPER A: "GEOMETRY ASSURANCE VERSUS ASSEMBLY ERGONOMICS-COMPARATIVE INTERVIEW STUDIES IN FIVE MANUFACTURING COMPANIES"

Paper A is an Interview study in five manufacturing companies that aimed to explore how assembly ergonomics and geometry assurance was handled during product development. This study was part of a larger interview study constituting 85 persons in five companies. 21 dedicated geometry assurance engineers, both in product development and manufacturing engineering, were given the same questionnaire as project engineers and the answers were evaluated, compared and discussed.

Since problems with assembly and geometrical quality often drive costs of poor quality the aim was to explore how and when decisions are made regarding this in the product development and if geometry assurance and assembly ergonomics are in conflict.

The results had several common conclusions and the most apparent was that the respondents had a high awareness about the implications of how poor assembly ergonomics result in poor geometrical quality and costs of poor quality. However, although the awareness is high, the respondents claim that someone else is responsible for this and the geometry assurance engineers do not take assembly ergonomics into consideration at all. In addition to this the geometrical requirements outrank the ergonomic requirements. Further, there are large differences between the product development and manufacturing engineering departments in knowledge of the problems.

Based on the answers in the study the conclusion can be made that the improvement focus should be in the early product development phases, to include the consideration of the assembly operation already when the first system solutions are created. This could be achieved by the addition of new tools, education and new ways of working cross functionally.

Method: Semi-structured interviews were used for this paper.

Main scientific contribution: New knowledge of the characteristics of how assembly ergonomics and geometry assurances are regarded in a product development process and how they interact.

Main industrial contribution: Increased understanding of how decisions are made regarding assembly ergonomics and geometry assurance in the product development. Highlight of possible areas to improve for better quality and less costs of poor quality.

4.1.2. Paper B: "Robust design and geometry assurance considering assembly ergonomics"

This study was a continuation of the interview study in paper A but with focus on the questions that were geometry assurance specific. The aim was to investigate how the geometry assurance engineers managed assembly ergonomics in detail. Focus was also set on finding out if the tool (CAT-tool) that they use in their daily work is up to the task to facilitate system solutions suitable for manual assembly in a paced line. The interviews were conducted in the automotive industry.

As determined in paper A, the awareness of how assembly ergonomics affect the product is high but this knowledge is not used when the system solutions (locating scheme and tolerances) are developed. Further, the ergonomic requirements posed on the system solutions are seen as an imposition that makes the solution worse. The issues are confirmed by the geometry assurance engineers in manufacturing engineering that have to try to quality assure the industrialization, the system solutions are not investigated enough when it comes to the assembly of them.

Further the manual assembly operations have been more complex over the latest decade and many mean the correlation between CAT simulations and actual outcome in production is low.

A number of factors that influence the geometric quality were identified by the respondents, with operator dependent assembly as the top factor.

The conclusions were that there is a large need for developing the CAT-tools to take assembly factors into consideration which was also an improvement that the geometry engineers would welcome. A first suggestion of a suitable method to do this based on the interview answers was discussed based on the existing stability analysis.

Method: Semi-structured interviews were used for this paper.

Main scientific contribution: New knowledge of the development of geometry system solutions in the automotive industry. Identified shortcomings of existing simulation methods in CAT. Suggestion of new methods to solve this.

Main industrial contribution: Identified problems that occur when the geometry system solutions are developed and industrialized in the automotive industry. Suggested changes in the organizational structure in the companies to support improved geometrical quality and listed factors that contribute to geometrical quality for manual assembly.

4.1.3. PAPER C: "OPERATOR RELATED CAUSES FOR LOW CORRELATION BETWEEN CAT SIMULATIONS AND PHYSICAL RESULTS"

In Paper A and B it was determined that assembly factors should be taken into consideration in early geometry assurance work but this is not done today and that this leads to low correlation between CAT simulations and actual outcome. In paper C this was tested by performing CAT simulations for 25 different manual assembly solutions and comparing the simulations results with measurements from running production. To complement this the geometry engineers that were responsible for the industrialization of these system solutions were interviewed about which issues that occurred during the production ramp up.

165 esthetical requirements were simulated in CAT showing a design well engineered, 81% were within in tolerance limits. However, a close inspection of the results shows that only 32% were truly calculated within tolerance, the rest were manually judged within tolerance. This was done because the geometry engineer lacked support in CAT tool to perform the simulations. In addition to this only 12% of the simulations contained some sort of process tolerances, implicating that neither the operator nor the assembly equipment adds any variation to the result.

Measurement data from production was obtained in the company measurement database, in total 8172 measures were used for the study. In total 61% of the esthetical requirements were outside of the original tolerance limits. This means a big discrepancy between CAT simulations and actual production outcome.

In order to understand this the geometry engineers that were responsible for industrialization of the system solutions were interviewed about the issues they had. The answers indicated that in 84% of the cases additional variation factors emerged in the industrialization that were not included in the CAT simulations.

Correlation analysis showed for instance that there was significant correlation between that not all factors that contribute to variation were included in the CAT simulation and non-fulfillment of tolerance limits in production.

A short term solution to improve correlation between CAT simulations and actual production outcome was suggested that involves measuring how much variation each assembly operation adds and always including this variation in the simulations. However, this will not improve quality, so a long term solution is to create system solutions that are truly plug-in, meaning that the operator does not add variation to the assembly. It is suggested to solve this by developing a method in CAT that assesses the complexity of an assembly.

Method: Case studies, Correlation analysis and semi-structured interviews were used for this paper.

Main scientific contribution: Showed that the current methods and ways of working in CAT are not sufficient to capture the influences of manually assembled parts. Suggested assembly complexity to be included in the existing methods and working procedures.

Main industrial contribution: Identified that the simulation results used to approve design solutions in the automotive industry today are not sufficient. Suggested a short term solution that can be applied directly.

4.1.4. PAPER D: "A MODEL FOR CALCULATION OF THE COSTS OF POOR ASSEMBLY ERGONOMICS"

The purpose of this paper was to determine the costs that are associated with poor assembly ergonomics, what they consist of and how poor assembly ergonomics affect product errors.

47 different assembly tasks were chosen and a total of 47061 cars were analyzed for all types of errors that occurred due to manual assembly errors, both in the production plant and on the market. The costs and correction time for each error were also collected and analyzed.

Each assembly task was evaluated with respect to ergonomic load level, using the rating low, moderate and high. The analyses showed that the risk of errors increased 7.8 times when comparing high and low level of ergonomic load. However, the most important finding was that from low to moderate level the risk of errors increases 5.8 times. Moderate levels of ergonomic loads are often seen as "almost ok", but this shows that even moderate levels of load increase the number of errors dramatically. There are consequently large gains to be made by decreasing the ergonomic load level, even from moderate levels.

Based on this a calculation model was developed for application in practice when a cost benefit analysis is needed to motivate a system solution that costs more but has lower ergonomic load level. The calculation includes all factors that contribute to costs of poor quality for manual assembly.

Method: Case studies, correlation analysis and controlled observations were used for this paper.

Main scientific contribution: A new method for calculation of the costs of assembly ergonomics, was developed.

Main industrial contribution: A method that can be used for cost benefit analysis when choosing system solutions that enables reduced number of errors and reduced costs of poor quality.

4.1.5. PAPER E: "ASSEMBLY FAILURES AND ACTION COST IN RELATION TO COMPLEXITY LEVEL AND ASSEMBLY ERGONOMICS IN MANUAL ASSEMBLY"

Based on the same data as in Paper D a second analysis was performed in this study. In this study the manual assembly complexity was evaluated against quality errors together with the relationship to assembly ergonomics.

The 47 assembly tasks were assessed using the 16 HC criteria from previous research and divided into 5 complexity levels from low to high.

The quality data was analyzed to find correlations between different components and complexity/ergonomic load level. Significant correlation was found for instance between:

- Assembly ergonomics and Complexity
- Complexity and assembly time
- Complexity and number of failures (errors)
- Complexity and costs of poor quality

The conclusions were that the more complex a manual assembly operation is, the more errors which will occur during assembly and the more expensive it will be to correct the errors. However, which of the 16 HC criteria that is the most important was not possible to determine so all 16 criteria need to be regarded when the assessment is done.

Method: Case studies and correlation analysis were used for this paper.

Main scientific contribution: New knowledge about how manual assembly complexity influences quality and costs of poor quality was gained.

Main industrial contribution: Gained knowledge about how to assess manual assembly complexity proactively to decrease errors and reduce the number of errors during assembly.

4.1.6. Paper F: "Geometrical robustness analysis considering manual assembly complexity"

Based on the results from papers A-E, showing how assembly complexity and assembly ergonomics influence product quality but are not taken into consideration when defining the system solutions, a need is identified. In addition to this it has been identified that all factors that contribute to variation are not included in CAT variation simulations and that the support for taking the assembly process into consideration is weak in the CAT-tools.

In this paper a new robustness value is introduced, that incorporates both sensitivity to variation and manual assembly complexity to form a total robustness for the entire system. The new robustness value is formed by normalizing both the stability analysis and the manual assembly complexity to a value between 0 and 1. A RMS operation is then performed on these two values to calculate the robustness. The method is implemented in the CAT tool RD&T as a demonstrator and tested on a simplified industrial case with promising results.

The new robustness value and calculation method will create awareness of assembly problems in early phases of product development and enable the development of system solutions with increased geometrical robustness.

Method: A case study was used in this paper.

Main scientific contribution: New robustness value for manually assembled parts.

Main industrial contribution: New method and tool for early geometry assurance and robust design that enables increased geometrical robustness. Tested on an industrial case.

4.2. THE RESULTS IN THE CONTEXT OF A VIRTUAL GEOMETRY ASSURANCE PROCESS

In this section the results in the appended papers are positioned in the geometry assurance process. The process has 3 main phases: the concept phase, the verification phase and the running production phase, see Figure 15.

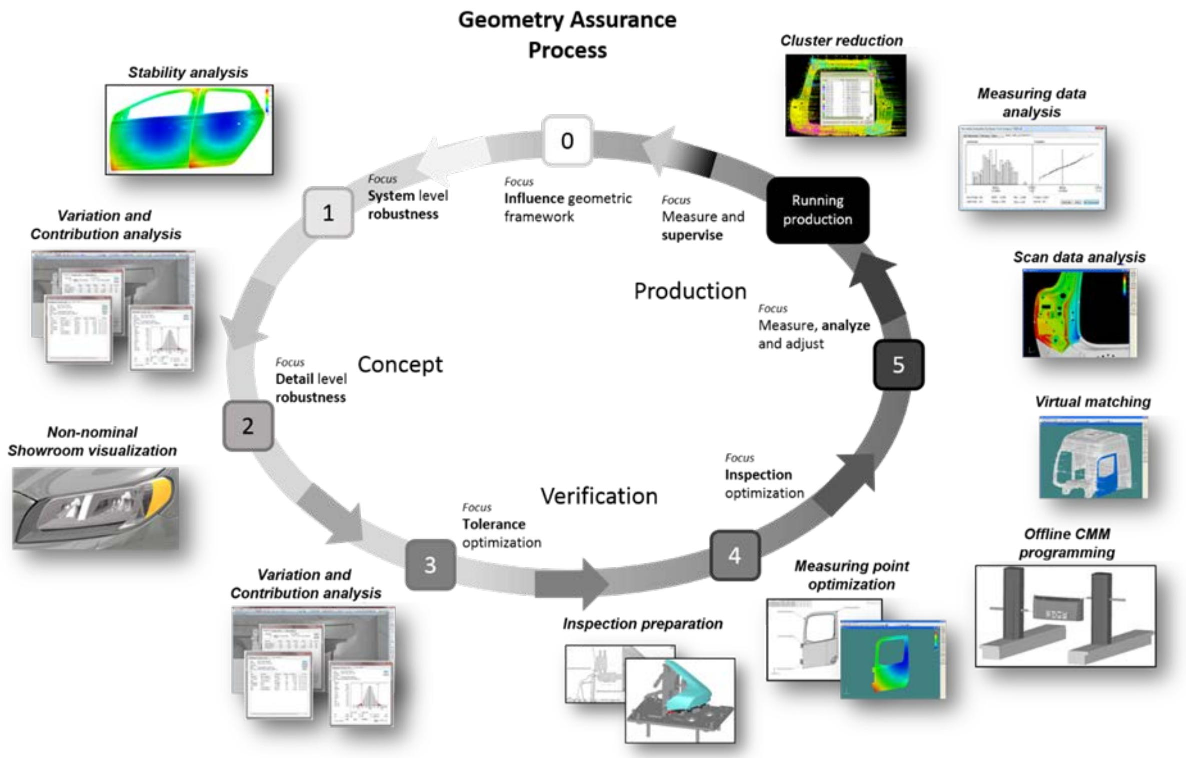

FIGURE 15: THE GEOMETRY ASSURANCE PROCESS

4.2.1. RESULTS FOR THE CONCEPT PHASE

Paper A and B survey how geometry assurance and assembly ergonomics are handled during product development with focus on the work that is carried out in the concept phase.

Paper C compares the result from the CAT simulations in the concept phase with the result from the running production phase.

In the concept phase the focus is set on creating a robust geometry system solution using the stability analysis and predicting variation using the variation analysis. These three papers penetrate how this work is carried out, which problems exist and how accurate the predictions are.

Paper D presents a calculation model for costs of poor quality from assembly ergonomics in the running production phase. The calculation model is based on data from the running production phase but is aimed at being used proactively in the concept phase when selecting the system solution to justify costs for a solution that will improve both ergonomics and quality.

Paper E verifies that manual assembly complexity influences product quality and should be included in early product development to support the selection of system solution.

These two papers present support methods for use in the concept phase when selecting system solutions and comparing different concepts with each other.

Paper F introduces a new robustness value and a tool for using it during robust design. The tool supports early geometry assurance in the concept phase to optimize the robustness of the system solution.

4.2.2. RESULTS FOR THE VERIFICATION PHASE

During the verification phase the chosen system solutions are verified and adjusted to be prepared for running production and any problems are solved.

The methods described in paper D, E and F can be used reactively in this phase to identify possible problem factors and test new or adjusted system solutions before changes are made to the assembly.

4.2.3. RESULTS FOR THE RUNNING PRODUCTION PHASE

In the running production phase the focus is to maintain a stable process and quality and monitor the geometrical requirements.

If problems should remain in this phase the methods described in paper D, E and F can be used reactively to identify possible problem factors and test new or adjusted system solutions before changes are made to the assembly.

4.3. INDUSTRIAL IMPLEMENTATION OF RESEARCH RESULTS

As mentioned previously a part of the Wingquist research process is that the results should be industrially implemented as much as possible. The research in this thesis has been done in close cooperation with the industry and the results have been continuously presented and distributed to the industry.

- Papers A and B: This research was done in close cooperation with several companies. The interviews were done onsite at the companies.
- Paper C: This research was done in close cooperation with Volvo Car Group and most of the work was done on site at Volvo.
- Papers D and E: This research was done in close cooperation with Volvo Car Group and most of the work was done on site at Volvo. The methods and calculation model is evaluated for implementation at Volvo car Group, Volvo AB and Scania CV AB.
- Paper F: This research was done in close cooperation with Volvo Car Group and most of the work was done onsite at Volvo. The new robustness value is implemented as a demonstrator in the commercial software RD&T and is currently being evaluated at Scania CV AB and Volvo AB for implementation. The new robustness value has been tested on an industrial case.

5. DISCUSSION

In this chapter, the answering of the research questions and the relevance of the used research methodology are discussed. The contribution this work makes to new knowledge is also considered.

5.1. ANSWERING THE RESEARCH QUESTIONS

The research questions will be answered one question at a time.

- *RQ1: How does manual assembly affect product quality and ergonomics?*

This question is addressed in papers A, B, D and E.

In Paper A and B a number of interviews were conducted in several companies to get a broad perspective on this. In paper D and E quality data from production was used to quantify how manual assembly affects both quality and the operators working conditions. Based on these studies several factors that influence both quality and ergonomics were identified. Many of these factors can originate from the product design. The question has been answered, however if further studies are performed more factors could probably be found.

- *RQ2: How can assembly complexity be considered in early development phases?*

This question is addressed in papers B, C, E and F.

In paper B, C and E methods to perform this are presented discussed and tested and in paper F a method is suggested and implemented in the CAT software RD&T. The method is based on manual assembly complexity affecting the geometrical quality. This answers the question partly, but alternative methods to do this may be applicable.

- *RQ3: How can manual assembly factors be considered in CAT?*

This question is addressed in papers B, C and F.

In paper B and C, the problems with the existing CAT simulations and tools were identified. Solutions were suggested and discussed in both papers and in paper F a new robustness value was introduced that included both sensitivity to variation and manual assembly complexity. The new robustness value was implemented and tested as a new method and calculation function in the CAT software RD&T. The method in paper F gives one answer to the question, however more answers could probably be found. The method is also not fully verified.

- *RQ4: How can operator variation be included in CAT?*

As mentioned previously this research question has not been addressed in this thesis but will be treated in the PhD thesis.

5.2. DISCUSSION OF THE RESEARCH APPROACH

In DRM the success criteria are central and in focus. The success criteria should be measurable and have defined metrics. However, the usage of numerical metrics can be problematic when measuring the success of a new computer aided design tool or method (Eckert et al., 2004). Another way of measuring the success criteria could be to assess the value of the tools and methods in the industry (Eckert et al., 2004). This also presents a problem due to the fact that new methods and tools can take a long time to be evaluated in their correct context. For example, an automotive product development project can take 3-4 years to perform using a new method and then another year to collect enough data in running production to measure the success.

The work in this thesis has been conducted in close cooperation with the industry continuously feeding them with results and ideas through seminars, case studies and demonstrators. This creates a high awareness of the research and also guarantees the usability of the results. To support this the Wingquist research process also enforces industrial feedback and demonstrators. During the research the industrial feedback has been very positive and the methods and tool developed have been highly valued in the industry due to the fact that they solve an existing problem and improve the product.

Due to this the chosen method, DRM, together with the Wingquist research process seem to be adequate choices for this research.

5.3. EVALUATING THE QUALITY OF THE RESEARCH

In order to evaluate the quality of the research that is presented in this thesis two criteria will be used to quantify the quality, verification and validation. In this context this means to internal consistency (verification) and the justification of claimed knowledge (validation) (Pedersen et al., 2000)

The results described in chapter 4 can be summarized as three parts; descriptive results, prescriptive methods and tools and knowledge of how manual assembly affects the product quality. Because these are different results two different approaches are needed to evaluate the quality of the research.

5.3.1. DESCRIPTIVE RESULTS

The descriptive research in this thesis has mainly been performed with a qualitative approach to capture the industrial reality of the design of products that are manually assembled. In this type of research 4 steps are needed to ensure validity (Yin, 2009).

- Internal validity, ensuring that respondents communicate their perspective in an unbiased way to the researchers. During the studies there was no evidence that the respondents were influenced by the recording device or the environment. The answers also indicate that the response was genuine.
- External validity, ensuring that the results of the studies can be applied and generalized outside of the context of which they were obtained. The studies were partly performed in companies that are not in the automotive industry and this ensures some possibility to generalize the results but the main focus has been the automotive industry and the results are mostly applicable here.

- Construct validity, ensuring that the correct measures are used for what is being studied. In this thesis the companies and manual assembly products have been studied. In each company a broad selection of respondents has been used in several positions throughout the companies including all geometry engineers available. Further, the selection of companies has been chosen so that they are relevant for what is studied. Together with recording and transcribing every interview the construct validity is secured.
- Reliability, demonstrating that the operations of a performed study can be repeated with the same results. In this research both how companies work at the time of the study and semi structured interviews with employees have been performed. The interviews have been conducted in the same order and in similar ways on all occasions, but it could be possible that another researcher performing the interviews could influence the answers somewhat. The interpretation and analysis of the answers could also differ slightly between researchers but the studies have been performed in such a way that it is very likely the results will be similar.
  The questions used in the semi-structured interviews were formulated with the industrial need and research gap as a framework. In addition to this the interviews where aimed at giving useful information for answering the research questions. All the questions were discussed and formulated with the aid of senior researchers and experts in the participating companies.

5.3.2. Prescriptive Methods and Tools and Knowledge about how manual assembly influences the Product Quality

These results have been verified by using Buur´s theory that suggests the use of logical verification and verification by acceptance for research that has many influencing factors, such as product design (Buur, 1990).

Logical verification according to Buur means that the research should have:

- Consistency: no internal conflict between individual elements of the research.
- Coherence: well established and successful methods agree with the results from the research.
- Completeness: observations can be explained or rejected by the theory.
- Ability to explain phenomena: case studies and data can be explained using the results.

The research results presented in this thesis are based on existing methods, tools and theories and well-known research within the field of geometry assurance and quality control. Several individual methods and theories are explored and generated in paper C, D, E and F. The methods and data that are used are widely used within the industry and accepted as best practice. Validation of consistency, completeness and coherence is ensured by literature studies of existing methods and theories. Performed case studies in industry also explain the generated results.

Verification by acceptance according to Buur:

- The generated theory is acceptable to experienced engineers.
- Suggested methods and tools are accepted by expert users within the field.

As mentioned in Chapter 4, the results are presented both for researchers and industry and accepted by them. The method in paper F has been implemented in the software RD&T and is currently being evaluated in industry with promising results. Methods in paper E and D have also been accepted by industry and are also a part of their toolbox in product development.

All appended papers have been peer reviewed by scientific referees and presented at scientific conferences and seminars including industrial reference boards.

5.4. Scientific contribution

The different scientific contributions have been described in section 4 and a summary of them will be provided here.

The general contribution in this thesis is *increased knowledge about how manual assembly is considered in the product development, how it affects the geometrical quality of the product and how the geometrical quality of the product can be improved*.

In addition, the following contributions have been made:

- Showed that the current methods and working procedures in CAT technics are not sufficient to capture all contributors to variation. Suggested assembly complexity to be included in the existing methods.
- Proved the more complex a manual assembly operation is, the more errors will occur during assembly and the more expensive it will be to correct the errors.
- A new method for calculation of the costs of assembly ergonomics.
- New robustness value for manual assembly parts.

Another important scientific contribution is the spread of new knowledge. The results have been presented in both conferences, journals and scientific seminars to create the awareness in academia of how manual assembly affects the quality of the product.

5.5. Industrial contribution

Industrial contribution has been described in detail in Section 4 but will be summarized here. The focus has been to generate methods and tools that can be used to improve the geometrical quality of manual assembly parts in early product development. This work has:

- Identified problems that occur when the geometry system solutions are developed and industrialized in the automotive industry. Suggested changes in the organizational structure in the companies to support improved geometrical quality and listed factors that contribute to problems with geometrical quality for manual assembly.
- Identified that the simulation results (from CAT) used to approve design solutions in the automotive industry today are not sufficient for manual assembly parts. Suggested a short term solution that can be used directly today.
- Proposed a method that can be used for cost benefit analysis when choosing system solutions, the method enables reduced number of errors and reduced costs of poor quality.

- Gained knowledge about how to assess manual assembly complexity proactively to decrease errors and reduce the number of errors during assembly.
- Proposed a new method and tool (in CAT) for early geometry assurance and robust design that enables increased geometrical robustness. This was tested on an industrial case.

6. Conclusions and Future Work

In this final chapter, the results are summarized and future work is outlined.

6.1. Conclusions

Costs of poor quality and problems with manual assembly in the automotive industry drive a need for more knowledge in this area and new methods and tools that can be used proactively instead of reactively. This is the main motivator for this research.

The research results in this thesis aim to generate new knowledge, tools and methods to facilitate geometry assurance of manual assembly parts. The research goal is improved geometrical quality for manually assembled parts.

The formulated research questions have been answered to some extent, however based on the results generated more research is needed to conclude on the impact of the suggested methods and tools, and to further refine them. Some conclusions can however be drawn:

- Product design has an impact on costs of poor quality and quality problems.
- Organizations, methods and tools used today in early product development have poor support for proactive consideration of manual assembly complexity.
- Decreasing manual assembly complexity leads to lower costs and less errors.
- Including consideration of manual assembly complexity in the early geometry assurance activities has the potential of improving the product and shortening the development time.

6.2. Future Work

During this research project several research gaps have been identified and many remaining questions still need to answered. Also one research question remains to be answered in the PhD thesis.

Examples of future work are:

- Continued research on the results in this thesis:
    - The new robustness value and its method described in paper F need to be further evaluated in more descriptive studies.
    - The results from this thesis need to be positioned in detail in a product development process in order to be industrially applicable. At the same time changes to the process, organization and responsibilities need to be further elaborated.
    - Expansion of the method in CAT to include multi part assembly operations (paper F).

- Variation simulation:
    - Tools and methods where manual assembly influences variation simulation need to be researched.
    - How much variation operators induce in different scenarios needs to be established and which factors affects this?
- Other uses of manual assembly complexity:
    - How can the manual assembly complexity assessment in early phases be used to improve assembly instruction in later phases?

7. REFERENCES

Bank, J., 1992, “The essence of total quality management”, Prentice Hall, New York, ISBN: 013284902x.

Blessing, L.T.M., Chakrabarti, A. & Wallace, K.M., 1998, "An Overview of Descriptive Studies in Relation to a General Design Research Methodology", In Ed.: Frankenberger, E., Badke-Schaub, P. & Birkhofer, H. *Designers - The Key to Successful Product Development*. Springer. pp.42-56.

Blessing, L.T.M., & Chakrabarti, A., 2009, "DRM, a design research methodology", New York, Springer, ISBN 978-1-84882-587-1.

Booker, J. D., Raines, M. and Swift, K. G., 2001, “Designing Capable and Reliable Products”, Butterworth-Heinemann, Oxford, ISBN 0 7506 5076 1.

Boothroyd, G. and Dewhurst, P., 1983, Product Design for Assembly Boothroyd Dewhurst, Wakefield, RI, USA, 1983.

Boothroyd, G., 1994, " Product design for manufacture and assembly", Computer Aided Desig, Volume 26, Issue 7, July 1994, Pp. 505-520.

Boothroyd, G., Dewhurst P., and Knight W., 2002, "Product Design for Manufacture and Assembly", 2nd ed. New York: Marcel Dekker.

Bracewell, R.H. et al., 2001, "A Methodology for Computational Design Tool Reseach", In *Proceedings of International Conference on Engineering Design, ICED'01*. Glasgow, 2001.

Buur, J., 1990, "A theoretical approach to mechatronics design", Ph. D Thesis, Technical University of Denmark, Lyngby.

Cai, W., 2006, "Robust pin layout design for sheet-panel locating", *Int J Adv Manuf Technology*, 28, pp.486-94.

Chase, K. & Parkinson, A., 1991, "A Survey of Research in the Application of Tolerance Analysis to the Design of Mechanical Assemblies", *Research in Engineering Design*, 3, pp.23-37.

Coletti, P. & Aichner, T. 2011, "Mass Customization: An Exploration of European Characteristics", Heidelberg; New York, Springer.

Eckert, C., Clarkson, P.J. & Stacey, M., 2004, "The Lure of the Measurable in Design Research", In *International Design Conference - Design 2004*. 18-21 May, Dubrovnik, Croatia, 2004.

ElMaraghy, W. H., and R. J. Urbanic. 2004. “Assessment of Manufacturing Operational Complexity.” CIRP Annals – Manufacturing Technology 53 (1): 401–406.

Elmaraghy, H., Samy, S. N. & Espinoza, V. A, 2010, "Classification Code for Assembly Systems", LIEN, T. K., ed. 3rd CIRP Conference on Assembly Technologies and Systems, June 1st-3rd, 2010, Trondheim, Norway. Tapir Uttrykk.

ENDSLEY, M. R., 1997, "Level of Automation: Integrating humans and automated systems", Proceedings of the 1997 41st Annual Meeting of the Human Factors and Ergonomics Society. Part 1 (of 2), Albuquerque, NM, USA. Santa Monica, CA, USA, Human Factors and Ergonomics Society, Inc.

Falck, A., 2007, "Virtual and Physical Methods for Efficient Ergonomics Risk Assessments – A Development Process for Application in Car Manufacturing", Thesis for the Degree of Licentiate of Philosophy. Department of Product and Production Development, Chalmers University of Technology, Göteborg, Sweden. Report no. 21. ISSN 1652-9243.

Falck, A. Örtengren, R. and Högberg, D., 2010, “The Impact of Poor Assembly Ergonomics on Product Quality: A Cost Benefit Analysis in Car Manufacturing”, Human Factors and Ergonomics in Manufacturing & Service Industries 20(1), pp. 24-41.

Falck, A.-C. & Rosenqvist, M. 2012, "Relationship between complexity in manual assembly work, ergonomics and assembly quality", Ergonomics for Sustainability and Growth, NES 2012 Stockholm, Sweden.

Fasth, Å. & Stahre, J., 2008, "Does Levels of Automation need to be changed in an assembly system? - A case study", The 2nd Swedish Production Symposium (SPS). Stockholm, Sweden.

Fasth, Å., Stahre, J. & Dencker, K, 2010, "Level of automation analysis in manufacturing systems" Proceedings of the 3rd international conference on applied human factors and ergonomics, 2010 Miami, florida, USA.

Fujimoto, H., Ahmed, A., 2001, "Entropic Evaluation of Assemblability in Concurrent Approach of Assembly Planning", In Proceedings of the IEEE International Symposium on Assembly and Task Planning, pp. 306-311.

Fässberg, T., Fasth, Å., Hellman, F., Davidsson, A. & Stahre, J., 2011, "Interaction between Complexity, Quality and Cognitive automation", CIRP Conference on Assembly Technologies and Systems, 2011.

Harrington, H.J., 1987, “Poor Quality Cost”, New York: Dekker, ISBN 0-8247-7743-3.

Hong, Y. & Chang, T.C., 2002, "A comprehensive review of tolerancing research", *International Journal of Production Research*, 40(11), pp.2425-59.

Hong, Y. & Chang, T.C., 2003, "Tolerancing algebra: A building block for handling tolerance interactions in design and manufacturing", *International Journal of Production Research*, 41(1), pp. 47-63

Hu, S. J., Zhu, X., Wang, H. & Koren, Y. 2008, "Product variety and manufacturing complexity in assembly systems and supply chains", CIRP Annals - Manufacturing Technology, 57, 45-48.

Ihantola, E.-M. & Kihn, L.-A., 2010, "Assessing the quality of case studies", Proceedings of the 3rd Qualitative Research Conference 1-3 June 2010 2010 University of Vaasa, Finland.

Jami, J. S., Gaurav, A., Zhengshu, S., & Joseph, D., 2007, " Navigating the Tolerance Analysis Maze", Computer-Aided Design and Applications, 4(5), pp 705-718

Lööf, J., 2010, "Managing Geometrical Variation through Optimization and Visualization", Gothenburg, Sweden: Ph D Thesis, Chalmers University of Technology.

Lööf, J., Söderberg, R. & Lindkvist, L., 2009, "Optimizing Locator Position to Maximise Robustness in Critical Product Dimension", In *Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE*. San Diego, California, 2009.

Mattsson, S., Gullander, P., Harlin, U., Bäckstrand, G., Fasth, Å., Davidsson, A., 2012, "Comparing quantifiable methods to measure complexity in assembly", 45th CIRP Conference on Manufacturing Systems 2012.

Mattson, S., Karlsson, M., Fasth-Berglund, Å. and Hansson, I., 2014, "Managing production complexity by empowering workers: six cases. Variety Management in Manufacturing", Proceedings of the 47th CIRP Conference on Manufacturing Systems.

Miles, B L. and Swift, K G. 1992, "Working together", Manuf. Breakthrough (Mar/Apt 1992)

Nigam, S. & Turner, J., 1995, "Review of statistical approaches to tolerance analysis", *Computer-Aided Design*, 27(1), pp.6-15.

Pedersen, K., Emblemsvåg, J., Bailey, R., Allen, J. K., & Mistree, F., 2000, "Validating Design Method and Research: The Validation Square", Proceedings of DETC 2000 ASME Design Engineering Technical Conferences, September 10-14, 2000, Baltimore, Maryland, USA

Rice, J. A., 2006, "Mathematical statistics and data analysis" 3rd Edition, Duxbury Press, ISBN: 9780495118688

Richardson, M., Jones, G., Torrance, M., Baguley, T., 2006, "Identifying the task variables that predict object assembly difficulty", HUMAN FACTORS, Fall 2006, Vol. 48, no. 3, pp. 511-525.

Rekiek, B.; Lit, P.D., Delchambre, A., 2000, "Designing Mixed-Product-Assembly Lines", IEEE Transaction. Robotics and Automation, 16(3), pp. 268-280.

RD&T Technology AB, 2016. *RD&T Manual ver 1.16*.

Samy, S.N., ElMaraghy, H.A., 2012, "Complexity mapping of the product and assembly system", Assembly Automation 32/2 (2012) 135-151.

Shah, R. and Ward, P T., 2007, " Defining and developing measures of lean production", Journal of Operations Management, 25, 2007, pp. 785–805.

Sivadasan, S., Efstathiou, J., Calinescu, A. and Huatuco, L. H., 2006, “Advances on measuring the operational complexity of suppliercustomer systems”, European Journal of Operational Research, 171, pp. 208-226.

Söderberg, R., 1998, "Robust Design by Support of CAT Tools", In *Proc. of the ASME Design Automation Conference*. Atlanta, USA, 1998. DETC98/DAC-5633. Fiskbensdiagrammet.

Söderberg, R. & Lindkvist, L., 1999, "Computer Aided Assembly Robustness Evaluation", *Journal of Engineering Design*, 10(2), pp.165-81.

Söderberg, R., Lindkvist, L. & Carlson, J.S., 2006, "Managing physical dependencies through location system design", *Journal of Engineering Design*, 17(4), pp. 325-346.

Söderberg, R., Lindkvist, L. & Carlson, J., 2006, "Virtual geometry assurance for effective product realization", In *Proceedings of 1st Nordic Conference on Product Lifecycle Management - NordPLM'06*. Gothenburg, Sweden, 2006.

Söderberg, R., Lindkvist, L., & Dahlström, S., 2006, "Computer-Aided Robustness Analysis for Compliant Assemblies", Journal of Engineering Design, 17(5), pp. 411-428.

Söderberg, R., Lindkvist, L., Wärmefjord, K. och Carlson, J., 2016, "Virtual Geometry Assurance Process and Toolbox", In proceedings of 14th CIRP Conference on Computer Aided Tolerancing CAT 2016. Gothenburg, Sweden, 2016.

Taguchi, G., 1986, "Introduction to quality engineering : designing quality into products and processes", Tokyo: Asian Productivity Organisation.

Taguchi, G., Chowdhury, S., & Wu, Y., 2005, "Taguchi´s quality engineering handbook", New Jersey: John Wiely & Sons.

Ullman, D. G., 2003, "The mechanical design process", New York, USA: McGraw-Hill Higher Education.

Yin, R. K., 2009, "Case Study Research: Design and Methods", Thousands Oaks, CA, SAGE.

Warnecke, H J. and Bassler, R., 1988 "Design for assembly - part of the design process" Annual CIRP Vol 37, No 1, 1988.

Wärmefjord, K., 2011, "Variation Control in Virtual Product Realization - A statistical Approach", Ph.D. Thesis, Chalmers University of Technology, Gothenburg, Sweden

Zhu, X., Hu, J., Koren, Y., Martin, S., 2008, "Modeling of manufacturing complexity in mixed-model assembly lines", Journal of Manufacturing Science and Engineering, 130, 051013-1-051013-10.

APPENDIX WITH APPENDED PAPERS