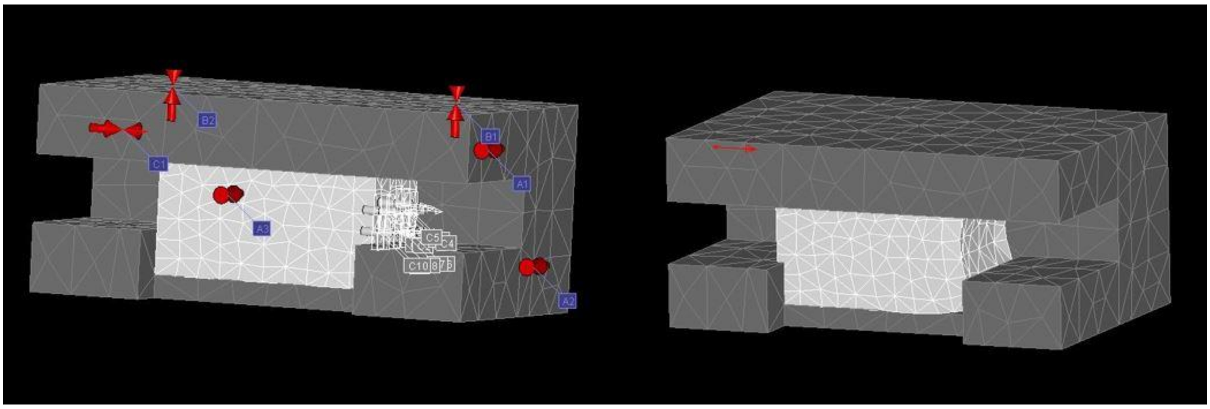
CHALMERS
UNIVERSITY OF TECHNOLOGY



PHYSICAL AND VIRTUAL EVALUATION OF OPERATORS' IMPACT ON GEOMETRY QUALITY FAILURE

Master's thesis in
Production Engineering

SOFIA WIKSTRAND

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

Physical and virtual evaluation of operators’ impact on geometry quality failure

Master’s thesis in Production Engineering

SOFIA WIKSTRAND

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

Physical and virtual evaluation of operators' impact on geometry quality failure
SOFIA WIKSTRAND

Department of Product and Production Development
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: + 46 (0)31-772 10 00

Abstract

From an industrial perspective, competitiveness call for superior quality and aesthetically appealing products. Quality and aesthetics can be affected by variation, which is consistently occurring in manufacturing processes. The department of Robust Design & Tolerancing at Volvo Car Corporation (VCC) create predictions of variation and in order for the department to create accurate predictions, all factors causing variation needs to be acknowledged. One unexplored contributor to the total variation is the variation caused by operators' during manual assemblies.

With a desire of wanting to take operator related variation during manual assemblies into account in the concept phase, physical and virtual tests have been performed making it possible to compare the results as a first step of research in this area. The future goal is to be able to quantify this contribution virtually, to avoid the need of creating prototypes and perform physical tests. To get to this point is a long road. It was also of interest to investigate whether it was possible to quantify operator related contribution to variation and to learn if it was possible to evaluate concepts virtually with regards to sensitivity in terms of assembly variation.

The results revealed that it was possible to quantify operator related contribution to variation, that there was no correlation between the physical and the virtual tests performed but that it was possible to evaluate the sensitivity of design concepts with regards to manual assembly.

Keywords: Geometrical variation, Robust design, RD&T, Manual assembly

Acknowledgement

This master's thesis was conducted at the department of Robust Design and Tolerancing at Volvo Car Corporation (VCC) and at the department of Product and Production development at Chalmers University of Technology. The author of the thesis, Sofia Wikstrand, has attended the master's programme in Production Management Engineering and the project was conducted during the spring of 2016.

Several obstacles have been encountered during this project, making this project educational in many ways. Support from both VCC and Chalmers made the obstacles possible to overcome. I would like to express my gratitude to my supervisors for the support given. Dag Johansson, supervisor at VCC, has throughout the entire process been available for questions, discussions and pep talks when needed. Lars Lindkvist, supervisor at Chalmers, contributed to this project by providing help with simulations, by always being able to answer questions on short notice and by providing food for thought, enhancing the thesis. I would also like to express my gratitude to the personnel at VCC that in some way or another has provided me with material or expertise needed.

Table of contents

1. Introduction

This section will briefly describe the reasons for initiating this project, what the intentions are and the delimitations encountered.

1.1 Background

Today, the rivalry in the automotive industry requires supreme quality to stay competitive. The quality of the final product is greatly affected by the variation accumulated in the development process, making this an important aspect to consider. Manufacturing activities consistently cause variation, implying that variation is inevitable (Söderberg, *et.al.,* 2006). Volvo Car Corporation (VCC) has to work proactively in this field in order to provide their customers with high quality products. The causes of variation are part variation, assembly variation and variation caused by the design concept (Söderberg, 1998). One of the main issues caused by variation regards aesthetical flaws since variation can cause unappealing split-lines, affecting perceived quality negatively (Forslund *et.al.,* 2011). To manage variation, robust solutions are established aiming at developing concepts that are insensitive regarding variation (Söderberg and Lindkvist, 1999). By developing robust design concepts, the geometrical quality can be improved.

VCC has a specific department working with establishing robust designs, called Robust Design and Tolerancing. The department is responsible for the geometry assurance work performed at R&D level by working solely in the software RD&T (Robust Design & Tolerancing), a software enabling variation simulation.

1.2 Theoretical gap

The accuracy of the predictions of variation performed by the department of Robust Design and Tolerancing could be improved by being able to quantify the operators' influence on variation during manual assemblies virtually. Hence, there is no method of doing this today indicating great potentials of improvement. During manual assemblies operators' can affect the position of the ingoing components, which can cause variation in the final product. Today, the department evaluate concepts virtually using part as well as process tolerances. The process variation is a collection of factors that can influence variation, and one of the factors is the variation caused during manual assemblies. At macro level the process variation is known, but each factor's influence at micro level is generally unknown. The variation caused during manual assemblies is estimated approximately, which affects the accuracy of the predictions negatively (Johansson, 2016). Being able to anticipate this variation with high accuracy in early phases virtually could enable ruling out concepts that are likely to be sensitive to assembly variation without having to create expensive prototypes to verify concepts physically. It would also enable improved accuracy of the predictions of the accumulated variation in the final product.

1.3 Objective

In a long term perspective, for VCC, the objective is to improve the concordance between the variation present in the final product and the variation estimated virtually in early stages of development by making more accurate predictions of variation stemming from manual assemblies. The objective of this master's thesis is to investigate whether it is possible to quantify operator related variation in manual assembles and to develop methods to perform physical and virtual tests to investigate whether a correlation of the physical and virtual results can be identified. By measuring how the position of articles deviates from their nominal position during repeated manual assembly and performing a virtual study, based on the results from the physical study, it is possible to investigate whether a correlation between the practical and the theoretical tests can be detected, which could be an important step in the development of being able to consider variation caused by operators' during manual assemblies in an early stage of product development. In addition to this, it is of interest to investigate whether it is possible to evaluate the robustness of the design concepts in an early stage of development when it comes to assembly variation.

The research questions can therefore be expressed as:

- Can operator related variation in manual assemblies be quantified?
- Is it possible to distinguish a correlation between virtual simulations of manual assemblies and actual manual assemblies?
- Can a virtual software be used to predict the robustness of a design concept, with regards to manual assemblies?

1.4 Delimitations

The master's thesis project was in progress during 20 weeks and began 18th of January 2016, a Gantt-schedule can be viewed in Appendix A.

During the physical and virtual tests performed in the project, the number of articles studied was limited by the resources given. Two different articles, for two car models, were studied. The methods used during the project was also limited by the resources available.

This project considers one specific approach of comparing virtual and physical results regarding manual assemblies. Hence, there are many alternative ways of performing such tests.

1.5 Outline of master's thesis

The first section of this report describes the background and the objective of this project. The following section, the literature study, provides the reader with relevant facts supporting the project. The literature study includes explanations of geometrical variation, tolerances, standard deviation, robust design, positioning systems, the geometrical assurance process, RD&T, operators and geometrical quality, coordinate measuring machines, the finite element method and compliance modelling. The third section explains the methodology used during the master's thesis. The fourth section reveals the results, followed by the fifth section that aims at discussing the results and the methods used. At last, conclusions and future research are presented.

2. Literature study

The literature study includes a description of geometrical variation, tolerances and standard deviation. It also aims at describing what characterizes a robust design and the importance of appropriately designed positioning systems. The geometry assurance process will be described as well as the software RD&T. Operators in relation to geometrical quality will be included and how a Coordinate Measuring Machine (CMM) operates will be presented shortly, since one have been used during the master thesis. A short and basic description of the Finite Element (FE) method is also included followed by a section describing compliance.

2.1 Geometrical variation

Manufacturing activities will to some extent always generate variation, causing items produced to vary from their nominal state (Söderberg *et.al.*, 2006). Reaching competitiveness in the industry today requires taking this into consideration since geometrical variation greatly influence quality and cost. The cost of geometry related errors propagate throughout the product development phases since small errors in an early phase can have severe consequences as the development progress (Chang and Gossard, 1997). The propagation of geometrical errors can also cause manufactured components not being able to reach the aesthetical or functional demands (Söderberg *et.al.*, 2006).

The main causes of variation are component variation, assembly variation as well as variation due to the design concept, see Figure 1 (Söderberg, 1998). Variation can thus stem from both shape and positioning of the components. Variation due to the shape of a component, component variation, implies the disparity among the nominal form and the form which it actually adopts. Variation stemming from the positioning of a component, assembly variation, involve the disparity among the nominal position and the positioning that actually takes place (Chang and Gossard, 1997). Assembly variation can also be explained as the deviation bounded by the ingoing components in the assembly (Cai, *et. al.*, 2015).

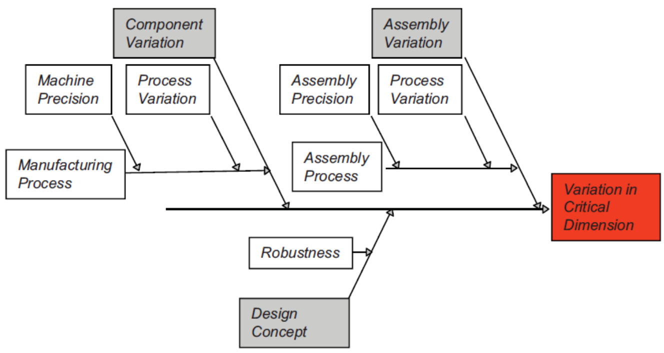


Figure 1. Main contributors to variation (Söderberg, 1998)

Variation can cause issues regarding the visual relation among components, known as split-lines. Variation related to split-lines can have an unfavourable impact on the perceived quality of the product. To manage split-lines effectively, part tolerances and robust solutions are adopted (Forslund *et.al.*, 2011). The two main defects that can occur in the split-line are gap and flush. Gap is the distance among two parts while flush is the distance among two parts in normal direction, see Figure 2. Issues with e.g. gaps can have severe consequences for companies operating in the industry. Besides the aesthetical aspect, too large or small gaps can result in commotion or leakage (Chang and Gossard, 1997).

Figure 2. Flush and gap (Lindkvist, 2016)

2.2 Tolerances

To limit variation, tolerances are used to determine whether a specific article is approved or not. Functionality, quality, cost and the equipment used in manufacturing should be considered when selecting the tolerance limits (Lilja *et.al*, 2011). Selecting a tight tolerance interval stresses high demands on the production process, results in high cost and should be used when the design is sensitive with regards to variation. A better alternative is to enhance the robustness to be able to select wider tolerances, enabling lower production expenditures (Söderberg and Lindkvist, 1999). The mid-point between the tolerance limits is known as the target value. When the target cannot be met, the mean value differs compared to the target value. Figure 3 illustrates the tolerance limits and the situation where the target value is not attained since the mean value ($\bar{x}$) deviates in relation to the mid-point (M) (VCS 5060,6, 2015).

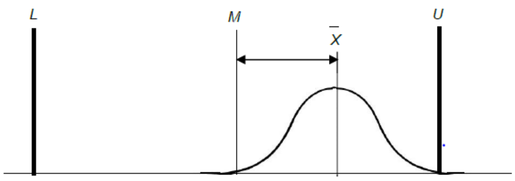


Figure 3. Tolerance limits, mean value shift (VCS 5060,6 2015)

2.3 Standard deviation

Standard deviation can be utilized to describe in what way a population varies in relation to the mean. The deviation among values in a data set and the mean is added and divided by the amount of observations, referred to as the variance, see Figure 4. The square root of the variance generates the standard deviation (VCS 5060,6 2015). The standard deviation is low when having a data set with values near the mean. Thus, a data set resulting in a substantial spread from the mean will result in a large standard deviation.

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

Figure 4. Standard deviation (VCS 5060,6, 2015)

2.4 Robust design

The designation *robust design*, refers to designs which are insensitive in terms of variation. Components with a robust design are less sensitive to variation, which can enable wider tolerance and thereby decreased cost (Söderberg and Lindkvist, 1999). Lindkvist (2016) explain that low output variation will be produced by a design that is less sensitive regarding variation, see Figure 5.

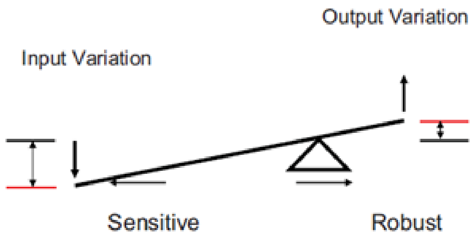


Figure 5. Illustration of a robust design (Lindkvist, 2016)

When robust designs are not accomplished the design will be sensitive to variation. This could lead to amplification of variation during the development process and can cause large output variation, see Figure 6.

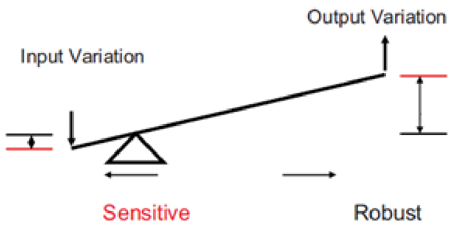


Figure 6. Illustration of a sensitive design (Lindkvist, 2016)

2.5 Positioning systems

The positioning system influence variation substantially as well as the robustness of designs (Söderberg and Lindkvist, 1999). A positioning system is established to fix the position of an article in six degrees of freedom and a widely used positioning system is the 3-2-1 system, see Figure 7. The 3-2-1 system includes three main positioning points (A1, A2 and A3) that hinders translation to occur in Z-direction and rotation to occur of X and Y. In addition to this, the positioning points B1 and B2 are used to restrict translation in X as well as rotation in Z. Furthermore, the positioning point C1 locks translation in Y (Söderberg *et.al.*, 2006).

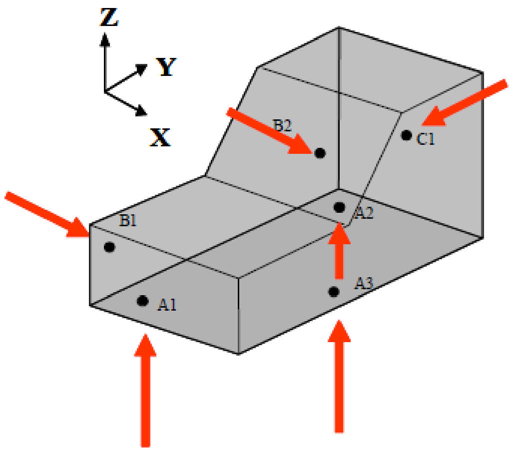


Figure 7. Positioning system (Söderberg et.al,. 2006)

A poorly established positioning system will generate large variation, thereby creating a design that is sensitive to variation. A robust design requires an appropriately selected positioning system, which includes spreading the positioning points as much as possible to create a large area between them. If the positioning points are selected in a way that restricts them to a small area of the component, the variation will escalate by the distance from the positioning points (Johansson, 2016).

2.6 Geometry assurance process

The geometry assurance process run through all stages of development. The initial phase to be acknowledged is the concept phase, where the concepts for both product and production are considered. The product concepts generated are evaluated to learn how well the concept endure the variation occurring during production. Virtually, the concepts are improved to create a solution that is as robust as possible. They are also evaluated in relation to the expected production system, using tolerances to attain an approximate result. Tolerances are therefore designated at part level with regards to the analysis made of the sensitivity of the concept. To gain knowledge of this sensitivity, a stability analysis can be suitable. A stability analysis will generate information of the robustness of the concept, determined by the positioning points. The stability analysis perform small adjustments of the positioning points and the final variation can be described for the entire concept. The result will indicate how the variation increase by the distance from the locators (Söderberg *et.al.*, 2006).

The following phase regards verification and pre-production and at this point the concept of the production and the product are evaluated in a physical manner. The results of the tests enables knowing what changes that could be suitable to reach improved results. The virtual perspective in this phase concerns to trim the concepts. The process of virtual trimming is performed to eliminate errors that concerns aesthetical and functional issues by altering the positioning points further (Söderberg, *et.al.*, 2006).

The third and last phase concerns production and this phase includes using the virtual perspective to control the actual production process. In this phase, the production is up-and-running and it is of great importance to quickly be able to detect errors. An error concerning geometry can be troublesome to detect. Root-Cause-Analysis (RCA) is used to detect errors occurring at specific stations, in fixtures or errors related to positioning. RCA convert variation existing in production into actions to alter the factors affecting the variation (Söderberg, *et.al.*, 2006).

2.7 RD&T

The software RD&T, Robust Design & Toleracing, can be used to simulate variation. The software enables deviations accumulated during manufacturing to be known in advance. Therefore, RD&T makes it possible to evaluate design concepts without having to create physical products or perform physical tests. RD&T can be used in the entire geometry assurance chain, starting with early development phases all the way to actual production. Positioning systems can be created and stability analysis can be performed to study the robustness based on the placement of the positioning points. Monte Carlo simulation enables the software to perform variation analysis. RD&T can also be used for compliance modelling and the software has a specific module for compliant modelling. The software has a Finite Element (FE) function, making this possible (RD&T Technology, 2016).

In RD&T it is possible to create contact points, see Figure 8. Contact points can be established to simulate that there is a conflict between two components. When creating contact points the user has to define the local and the target nodal points and which direction the contact point should adopt (Software Manual, 2015).

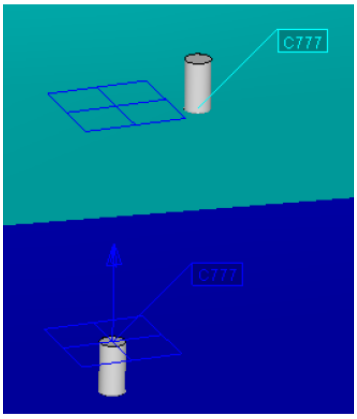


Figure 8. Contact points (Software Manual)

Weld points, locking all degrees of freedom, can also be created in RD&T, see Figure 9.

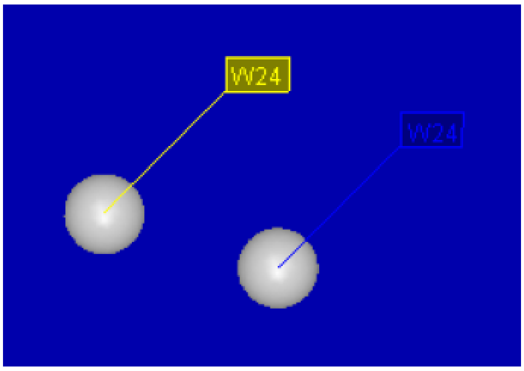


Figure 9. Weld points (Software Manual, 2015)

2.8 Operators and geometrical quality

Calculations in CAT software's do not take variation stemming from manual assembly into account, which affect the accuracy of the predictions of variation. Since the operators during manual assemblies are not consistently able to lock all positioning points as intended, it is challenging to estimate the variation stemming from the manual assembly process (Falck, *et.al.,* 2014). If the operator cannot position a part as expected, the geometrical outcome of the virtual and the actual world will differ. To improve the CAT simulations, this aspect needs to be taken into consideration. In order for the operators to succeed to position the component as expected, it is important that they are given the proper conditions. In assemblies where the operator is given no feedback when having reached the locating point or where it is hidden, it is difficult for the operator to succeed (Rosenqvist *et.al.,* 2013). If the production process is not being acknowledged in the development phase, geometrical issues can occur that later on can affect the product. The variation can lead to e.g. fitting related issues in further assemblies. Therefore, it is essential to reduce variation during the manufacturing process (Camelio, *et.al.,* 2003).

Rosenqvist *et.al.* (2014) claims that the quality of a product is greatly influenced by the assembly complexity. The authors use the word "assemblability", referring to ease of assembly. Assemblability includes advantageous conditions concerning e.g. positioning. To evaluate whether an assembly process is complex or not, the authors established "16 criteria for high manual assembly complexity (HC) considered as tricky and demanding operations", see Appendix B. To be able to classify the outcome of this evaluation there is a scale based on the answers of the questions, which divide the degree of complexity into five categories, see Appendix C.

2.9 Coordinate measuring machine (CMM)

Due to an increased importance of producing high-quality products, Coordinate Measuring Machines (CMMs) are commonly used in the industry today to judge the geometrical quality of a product. (Agapiou and Du, 2007). CMMs are entire systems, aiming at measuring coordinates of specific points using a moveable probe. In Figure 10 a CMM is shown and the black circle indicates the position of the probe. The general parts of a CMM are the actual machine, the probe used to measure and the software used for the measurements. The software receives information from the probe, which runs automatically, and the probe registers the position of the point to be measured in x-, y- and z-direction. The resolution of the CMM determines the accuracy of the measurements (Globalspec, 2016). To ensure that the CMM measures with high accuracy the machines have to be recertified every year (Agapiou and Du, 2007).

Figure 10. Coordinate Measuring Machine (CMM) (Direct Industry, 2016).

2.10 Finite Element method

To describe situations occurring in the field of engineering, differential equations are often used. Confronting these problems analytically is troublesome and therefore the Finite Element (FE) method can be used. The FE method operates numerically and solves the differential equations approximately. The differential equations can represent a specific issue of a domain and the FE method will split this domain into small elements, *finite elements*, solving the approximation for each element. Although the factors affecting the domain vary nonlinearly, this estimation can be based on a linear behaviour of each element. A mesh has been generated when considering these elements as a whole. The mesh can describe how the elements behave and reinforcement of the elements can generate the possibility of observing the movements of what is being studied. The estimation require that it is presumed that the variable investigated is known at specific areas of the elements, referred to as nodal points placed at the boundary of the elements. The FE method generates equation systems including a high number of unknown variables and matrix algebra is therefore utilized (Ottosen and Petersson, 1992).

The FE method generally includes the following steps:

1. Creating stiffness relation for every element.
2. Compilation of elements.
3. Create balance along all nodal points.
4. When reaching this step, referred to as assembling, the equation system is created for the entire body.
5. Boundary conditions are set to be able to work out the equation system.
6. In this step, the equation systems are solved.

2.11 Compliance modelling

As mentioned earlier, all components deviate from nominal shape. In addition to this, compliant components deform additionally throughout the assembly process. Currently, many computer-aided design programs only support components that are rigid, have nominal dimensions and are positioned nominally with the downside of not being able to predict variation properly. Therefore, compliance have to be considered since it can be a source of variation in assemblies. When non-rigid components distort in the assembly process, the variation of one component can spread to surrounding components. Figure 11 illustrates a component, component B, that is ideally produced but when the component is assembled it is not able to remain its geometry (Chang and Gossard, 1997).

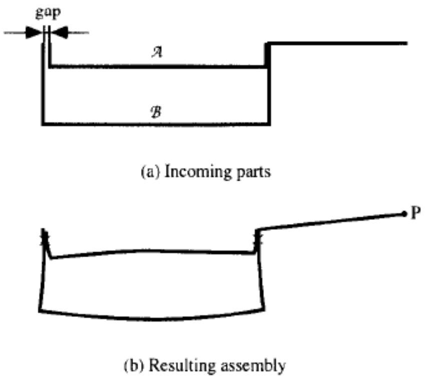


Figure 11. Non-rigid components (Chang and Gossard, 1997)

Compliant modelling enables the components studied to be deformed, requiring positioning systems that are over-constrained. When wanting to simulate compliant components, e.g. plastic components, it is not satisfactory to constrain the component in the same way as for rigid articles, since the behaviour of the material differs (Söderberg *et.al.*, 2008). RD&T has a specific module that is suitable for compliance modelling.

3. Methodology

In this section the methodology used during the master thesis will be explained starting at an aggregated level to later on explain each area in detail. The activities included in the project are in accordance to Figure 12. The literature study was performed to create a platform of knowledge, an important base during the project. The method also contains both a physical and a virtual study. These two studies had the same starting point, investigated the same issue with the intention to be able to compare the results among these two approaches in the end.

The **physical study** will be mentioned several times and refers to manual assembly activities performed in the pilot plant at VCC during the project. The objective of the physical study is to document variation stemming from manual assembly of a number of articles and to measure the force the operators' induced during assembly. The **virtual study** will also be mentioned and refers to the activities performed in virtual environments to illustrate the physical study. The idea of performing the two studies is to use the deviations measured in the physical study as input in the virtual study to be able to compare the forces generated virtually with the forces induced during the physical study, enabling a possibility to study the relation of the physical and the virtual results.

The sub activities for the physical and the virtual study will be explained further in coming sections. The assemblies in the studies regard attachment of the Glass Run Seal (GRS) and the Outer Waist Seal (OWS) to the door, in this case the left front door.

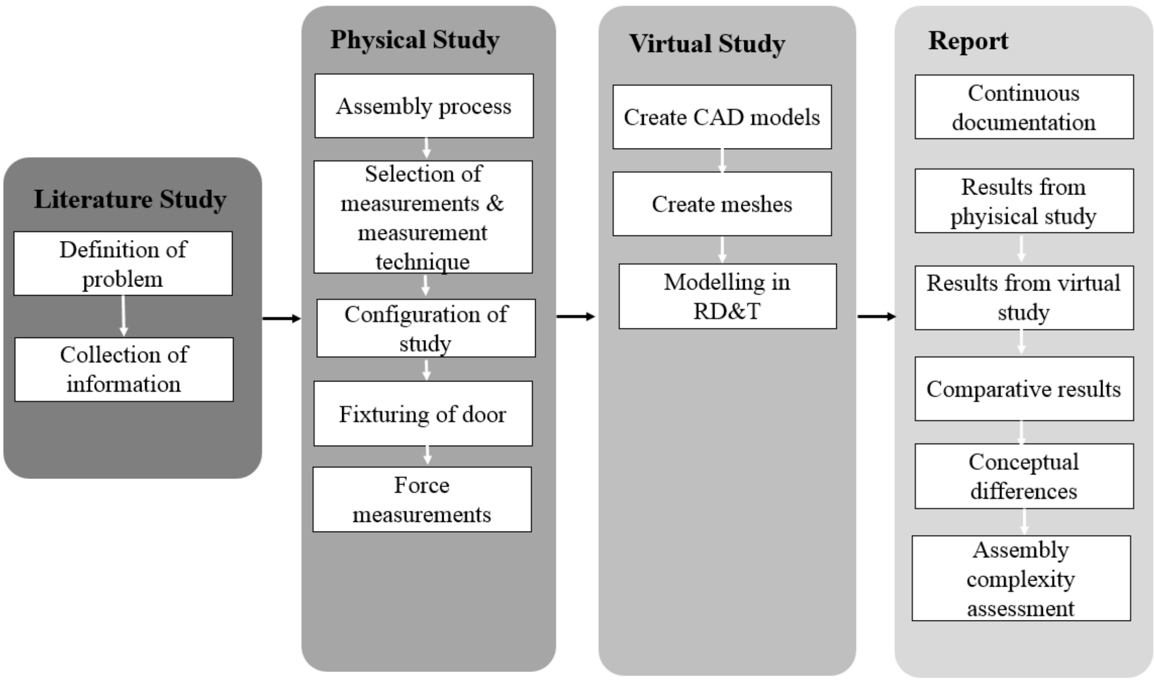


Figure 12. Methodology during the master thesis project

3.1 Literature study

When the problem definition of the project was set the areas included in the literature study were selected in order to support the research area. The areas included are:

- Geometrical variation
- Tolerances
- Standard deviation
- Robust design
- Positioning systems
- Geometry assurance process
- Operators and geometrical quality
- Coordinate Measuring Machine (CMM)
- Basics of the finite element method
- Compliance modelling

3.2 Physical study

The physical study included operators assembling the two components Glass Run Seal (GRS) and the Outer Waist Seal (OWS) repeatedly at a front door followed by a measuring procedure to document the deviation attained from the articles' nominal position. The study was performed for two different car models, car model A and car model B. From now on, the GRS and the OWS belonging to car model A will be denoted GRS_A and OWS_A. The same logic will apply for the GRS and the OWS for car model B, GRS_B and OWS_B. The force induced by the operators' was also measured. In order for the physical study to be executed, the following activities were performed:

- Assembly process identification
- Selection of measurements and measurement technique
- Configuration of study (operators, repetitions and material)
- Measuring with a Coordinate Measuring Machine (CMM)
- Fixturing of door
- Force evaluation

3.2.1 Assembly process

The position of the GRS and the OWS when mounted on the door can be seen in Figure 13 and the placement of the reference element is illustrated by the circles. Figure 13 illustrates the GRS, OWS and the door for car model A. This looks nearly identical for car model B and therefore only images for car model A will be shown. Both the GRS and the OWS are seals fixed to chrome strips and the assembly process starts with assembling the GRS, followed by assembling the OWS. Therefore, the procedure will presented in that order below.

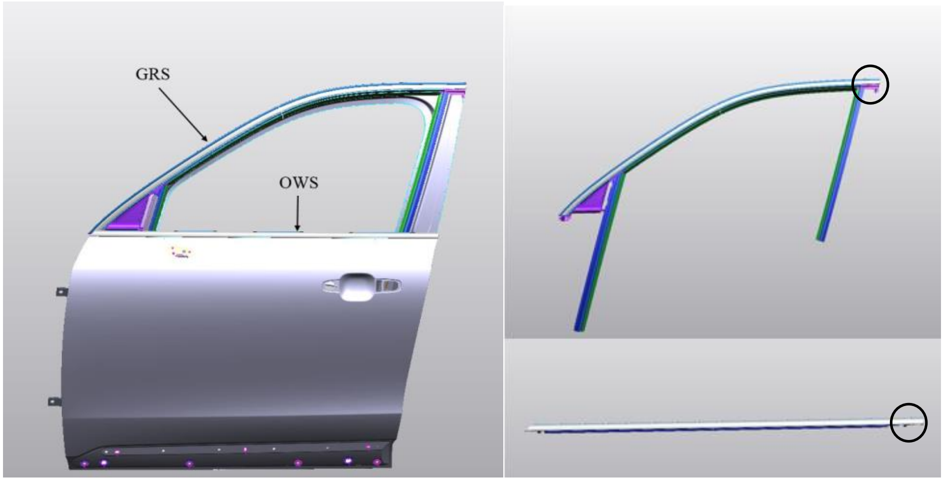


Figure 13. Left picture: GRS, OWS assembled on door. Upper right picture: GRS. Lower right picture: OWS.

The main characteristic that separates GRS_A and GRS_B is the reference element in x-direction, which can be seen in Figure 14. Therefore, the explanation of the assembly process will only include the assembly of the reference element. The purpose of the reference element is to lock the movement of the part in x-direction.

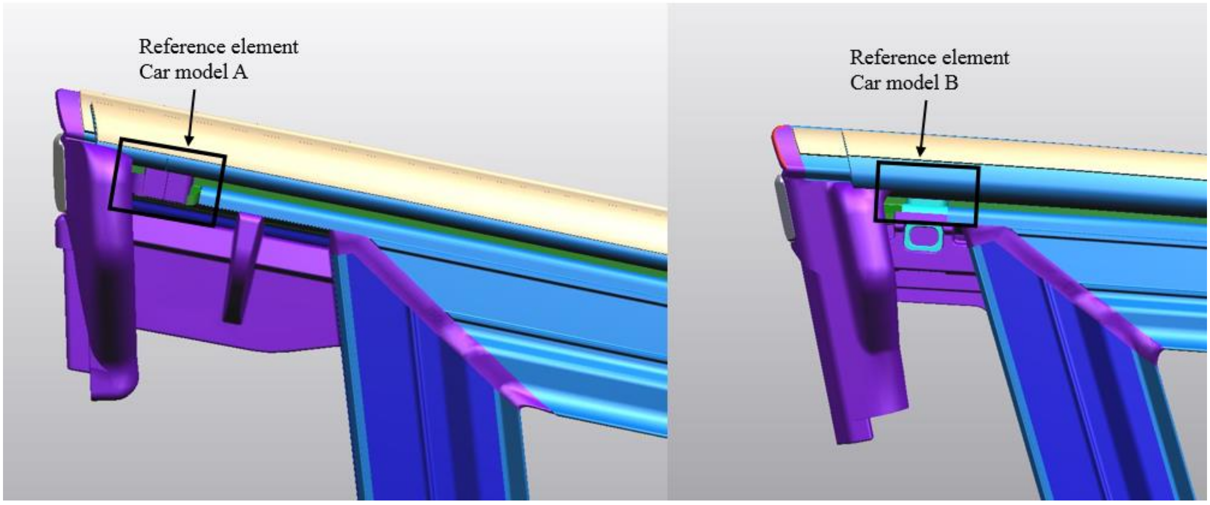


Figure 14. Reference elements of GRS_A *and* GRS_B

The material of the reference element differs between the models, see Table 1.

Table 1. Material properties

Article: GRS and OWS	Car Model A	Car Model B
Material	Santoprene	Polypropylene
Young's modulus (MPa)	2	1300

The GRS is assembled by pressing the reference element against a cut out in the door, where the reference element is enveloped by the cut out in the car door (C8450-0012, 2015). Figure 15 illustrates this process.

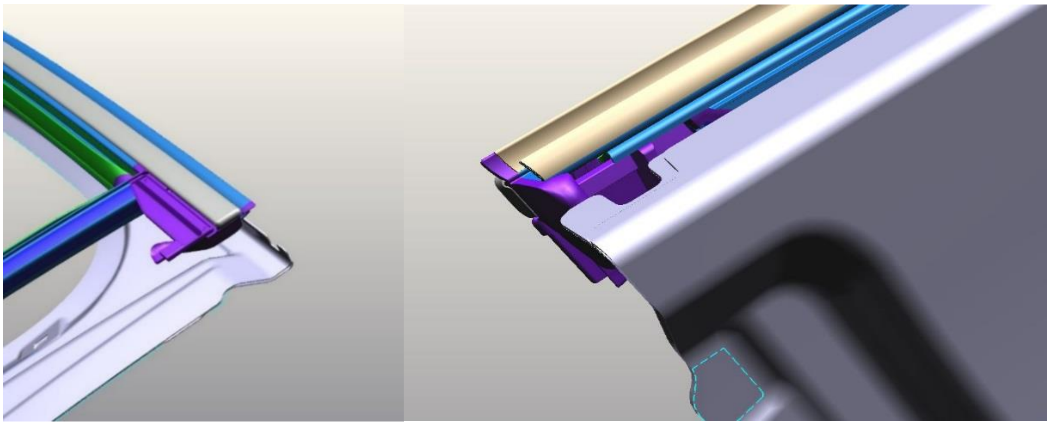


Figure 15. Assembly of GRS

The main difference separating OWS_A and OWS_B is the same as for the GRS, the visual difference can be seen in Figure 16.

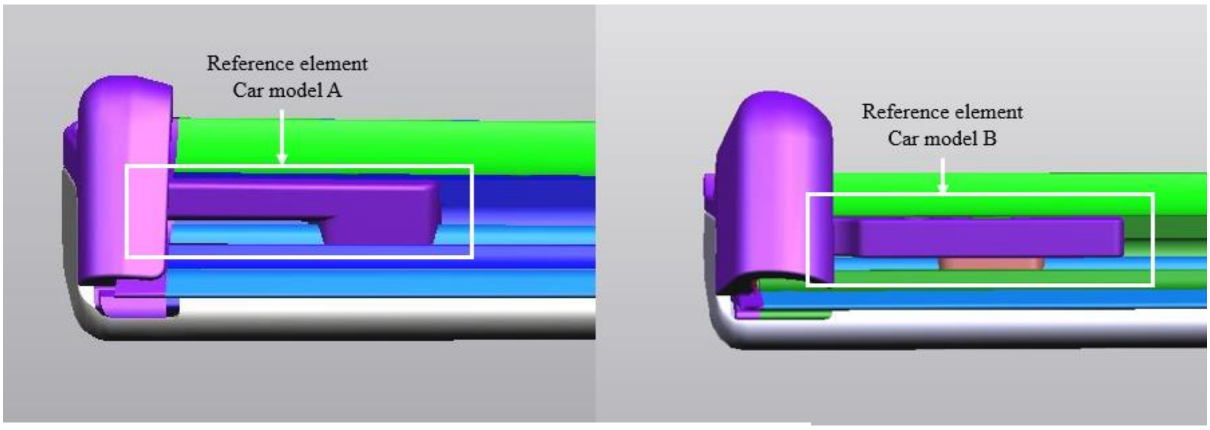


Figure 16. Reference elements of OWS_A *and* OWS_B

Assembling the reference element of the OWS is performed by pushing the reference element against the cut out in the door, which is placed in the rear area of the door, see Figure 17 (C8450-0001, 2015).

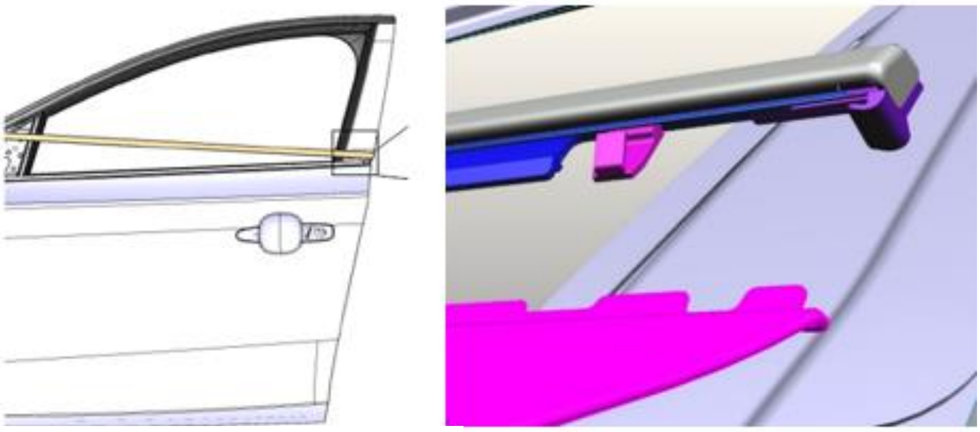


Figure 17. Assembly of OWS

3.2.2 Selection of measurements

Due to non-aesthetical results of the placement of the OWS and the GRS in production today the measurements were chosen in accordance to what has been observed as inadequate. The relation between the chrome strips on the front and rear door has been identified as an issue since it can affect customer satisfaction negatively, the placement of these can be seen in Figure 18.

Figure 18. Areas of interest (Volvo Cars, 2016)

The upper area is where the front and the rear GRS meet and the non-aesthetical relation identified can be seen to the left in Figure 19. The lower area is where the front and the rear OWS meet. The relation between the front and the rear OWS can also in many cases be seen as unappealing and can be seen to the right in Figure 19.

Figure 19. Left: GRS. Right: OWS

The chrome strips are fixed to the seals, which the reference elements are placed on. Thereby, the placement of the seals also determines the position of the chrome strips. It is clear that there are issues regarding gap in x-direction and therefore a measuring point located at the rear end of both articles was evaluated, see Figure 20. When the articles had been assembled, the position of the selected points were measured by the CMM in relation to the corresponding point in the nominal CAD model, thereby generating the deviation.

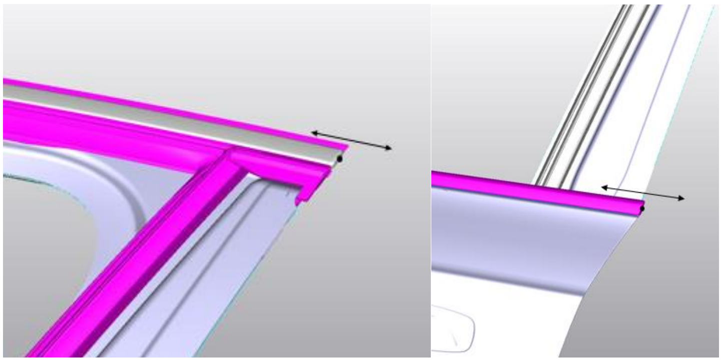


Figure 20. Left: measuring point at GRS. Right: measuring point at OWS

3.2.3 Configuration of study

The configuration of the study included selecting the number of operators to be included, number of repetitions performed, amount of material included etc. The configuration of the physical study differed somewhat for car model A and B due to restrictions of material, see Table 2. This resulted in the possibility of including several operators when studying car model A. Three operators were included with different gender, experience and dimensions. The operators' executed three repetitions each, nine repetitions in total. For car model B the access to material was restricted and therefore only one operator executed three repetitions.

Table 2. Amount of material, operators, repetitions

Context	Car model A	Car model B
Samples of GRS	9	3
Samples of OWS	9	3
Operators	3	1
Repetitions GRS	9	3
Repetitions OWS	9	3

One repetition equals assembling one GRS and one OWS, measuring the deviation and the force, see Fig 21.

Figure 21. Activities included in one repetition

The components risk breakage during assembly and disassembly. Therefore, each article was assembled only one time and then it was classified as discarded in order to avoid documenting variation stemming from e.g. broken reference elements. This limited the number of repetitions performed. Since part variation could contribute to the variation attained during the measurements, this was examined. The distance between the reference elements and the placement of the force was measured six times for all samples of the $\mathrm{GRS_A}$, $\mathrm{OWS_A}$, $\mathrm{GRS_B}$ and $\mathrm{OWS_B}$. This enabled an average value of the distance for each sample and they could then be compared to the average among all samples.

3.2.4 Fixturing of door

To mount the GRS and the OWS to the door, it needed to be attached to a fixture. Three components were used to position the door, two pillars and a plate. To the left, a plate was attached to one of the pillars with the intention to settle the position of the hinges of the door. The pillar placed at the rear end of the door positioned the door through clamps, see Fig 22.

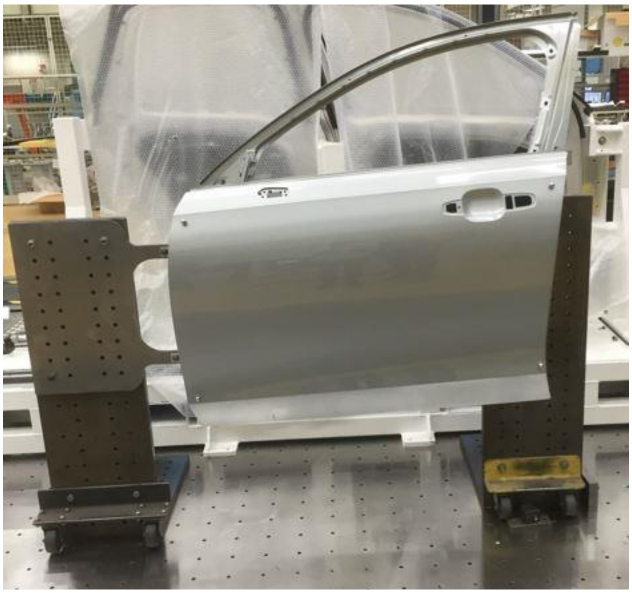


Figure 22. Fixturing of door

The plate used for car model A was borrowed from the pilot plant while the plate needed for car model B was modelled in CATIA V5 and then formed from sheet metal, see fig 23.

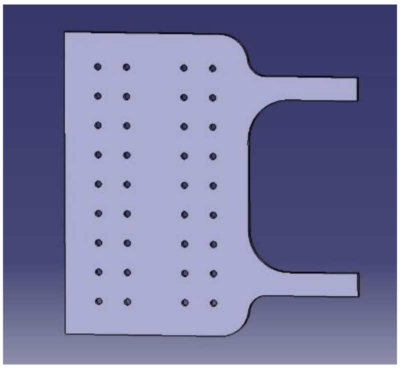


Figure 23. CAD model of plate

Although the door was positioned firmly there was a possibility of changing the position of the door during the assembly/disassembly. If this was not to be taken into consideration, it could influence the measurements since altering the position of the door would change the position of the measuring points. To eliminate this possibility, the CMM was utilized for resetting the position of the door. The resetting procedure needed to be done both after assembly and disassembly and was performed regularly for every repetition, see Fig 24.

Figure 24. Resetting activity

The activity of resetting was based on three spheres attached to the door, working as the reference points, see Fig 25. In order for the door to be aligned, the CMM complied with the spheres located at the door. By doing this, the position of the door itself did not have to be altered. Instead, the coordinate system of the CMM was matched to the position of the door. Besides the three reference spheres, a fourth sphere was used in order to further ensure the placement of the door.

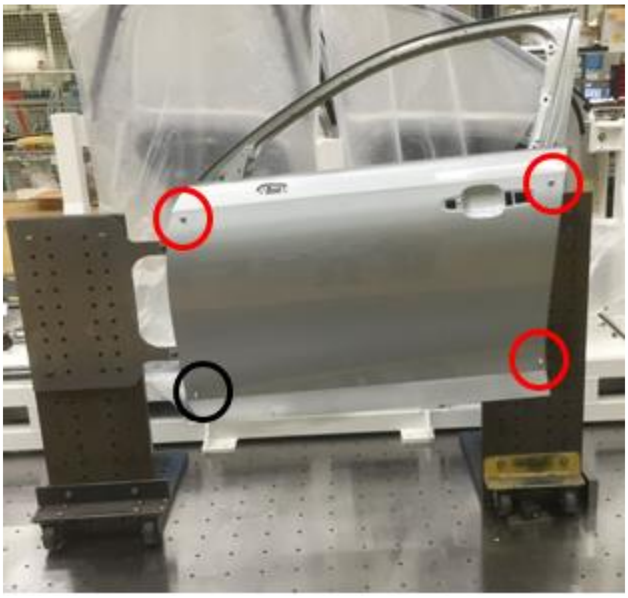


Figure 25. Reference spheres

3.2.5 Force measurements

Measuring the force induced by each operator with a dynamometer during actual assembly is complicated since the operators have to have their hands free to assemble. Therefore, every assembly of the GRS and the OWS was followed by a force estimation, see Fig 26. The force estimation was performed by pressing a pressure component fixed to a dynamometer at the already assembled parts. During the force estimation the operators were supposed to recreate the magnitude of the force induced during the actual assembly. The reason for pressuring against already assembled parts was to create the same environment for the operator as during assembly to enhance the accuracy of the force measurements.

Figure 26. Force test in relation to the process

The pressure components used, one to measure force on the GRS and one for measuring the force induced at the GRS, were developed to accommodate the proper direction of the force.

Observations was made in the factory in order to ensure the force direction. The pressure components were then designed accordingly, with a threaded hole in order to be able to attach them to the dynamometer. In Figure 27 the pressure components for both articles are shown with the arrow indicating force direction. See Appendix D and Appendix E for pictures of the pressure components.

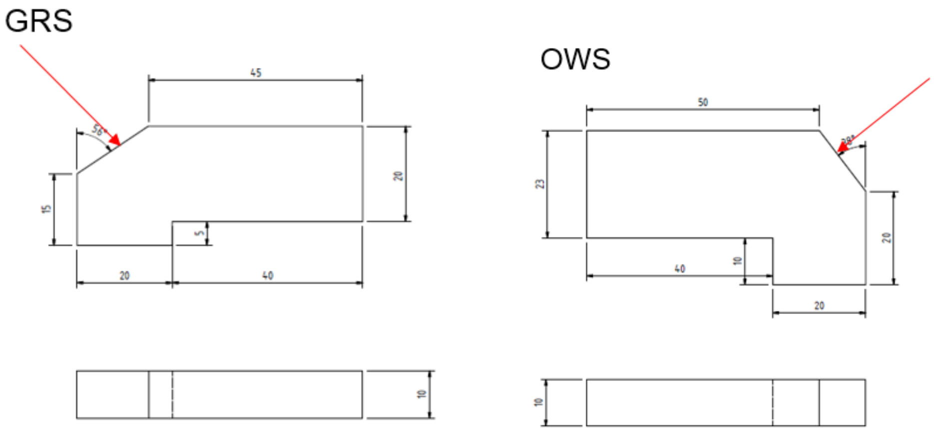


Figure 27. Drawings of pressure components GRS, OWS

In Figure 28 the operator is assembling the reference element in x-direction of the GRS against the door. After the assembly the operator regained the position and pressured the dynamometer with its pressure component in accordance to the force induced during assembly, see Figure 28.

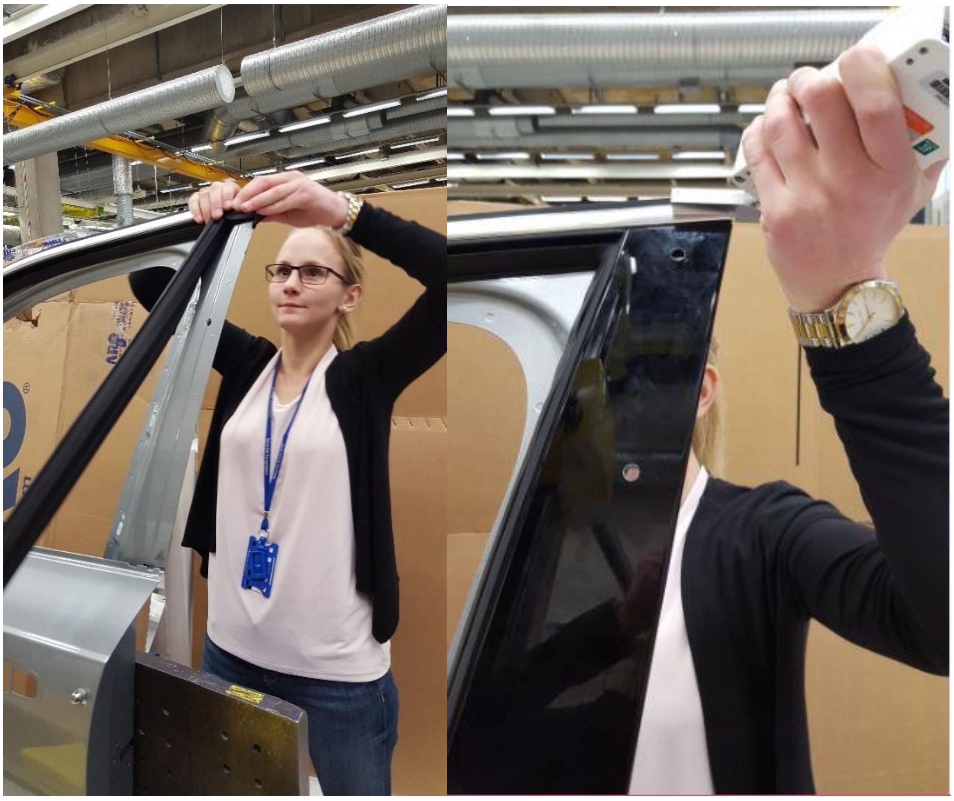


Figure 28. Left: Assembly of GRS. Right: Force estimation of assembly

In Figure 29 the operator is assembling the reference element in x-direction of the OWS against the door. After the assembly the operator used the dynamometer with its pressure component in accordance to the force induced during assembly, see Figure 29.

Figure 29. Left: Assembly of OWS. Right: Force estimation of assembly

A study was executed using seven operators in order to study the accuracy of the force evaluation. All seven operators were told to press the pressure component, with the dynamometer fixed to it, against a table and then repeat this six times. A reference round was performed first where the operators were told when they reached 45 N. Their task was then to try to reach this force, without receiving feedback, six times with ten minutes between each repetition.

3.3 Virtual study

The virtual study included three main stages including the GRS and the OWS for both car model A and car model B, meaning that four different articles underwent the following three stages:

- Establishing CAD models
- Meshing
- Modelling in RD&T

3.3.1 Establishing CAD models

In Figure 14 and Figure 16 the reference elements for the GRS and the OWS for car model A and B were illustrated. In this stage CAD models were established, in CATIA V5, in accordance to the reference elements. Models of the nearest surrounding of each reference element were also established. Thus, the entire components were not modelled, only the area of interest.

3.3.2 Meshing

After creating CAD models the work bench "Analysis and Simulation" in CATIA V5 was used to create meshes. The element size was decreased iteratively until it was no longer possible to implement the mesh in RD&T.

3.3.3 Modelling in RD&T

The idea of modelling in RD&T was to investigate whether it was possible to attain similar results virtually, as during the physical study, using the deviations attained during the assemblies as input and comparing the output in RD&T (force) to the forces documented in the physical study. This was performed for both car model A and car model B, enabling a comparison of the two. The young's modulus for the material of the reference elements of the articles differ and will therefore be set for each article in RD&T. To reach this state in RD&T the following steps were performed:

1. The bulk data mesh was uploaded for the reference element and the surrounding part and the meshes were checked by the program, see Figure 28. The box beside "Compliant Part" was checked, meaning that the modelling concerns a non-rigid part. The young's modulus (Elastic) were set for both components and a parent part, called Super part, was created that contained the reference element and its closest surrounding, see Figure 30.

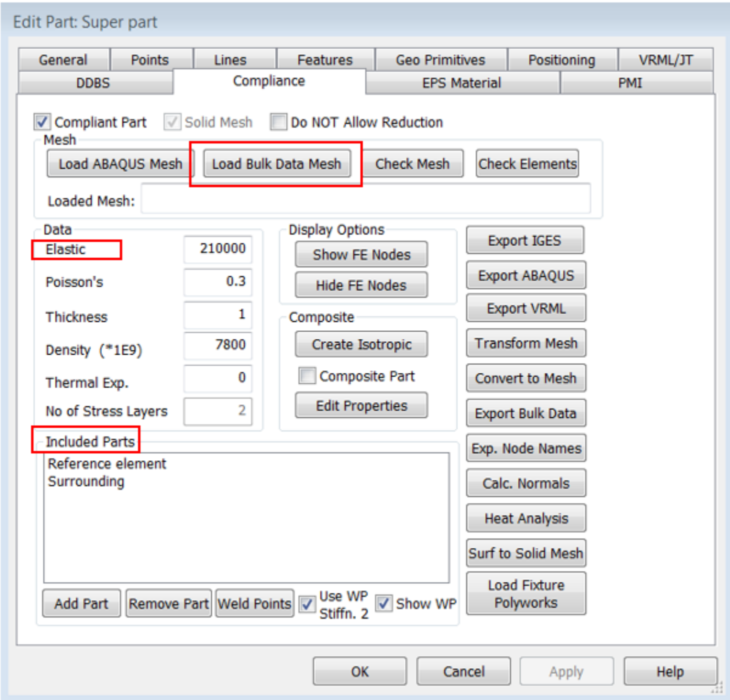


Figure 30. Compliance tab

2. The Super part enabled weld points to be set between the reference element and its surrounding, see Figure 31. This was performed to illustrate that the two parts are attached, in reality they are not joined by welds.

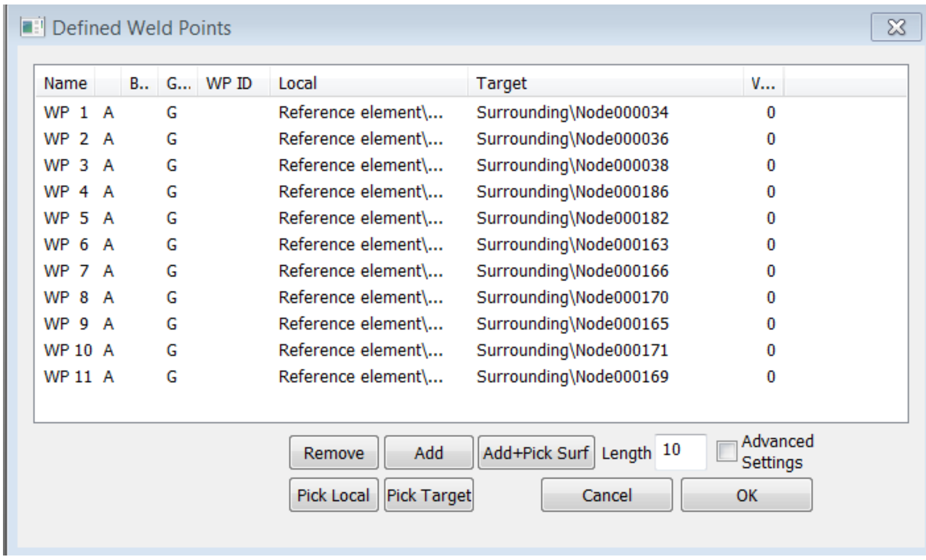


Figure 31. Weld points, local and target nodes

3. The Super part was positioned against a fixture, demonstrating the door to which it is attached, see Figure 32. The positioning point in x-direction was placed where the force was induced in the physical study. For compliant parts the positioning system "6 Direction" is used, meaning that six directions are determined beside the six local and target points (Software Manual, 2015).

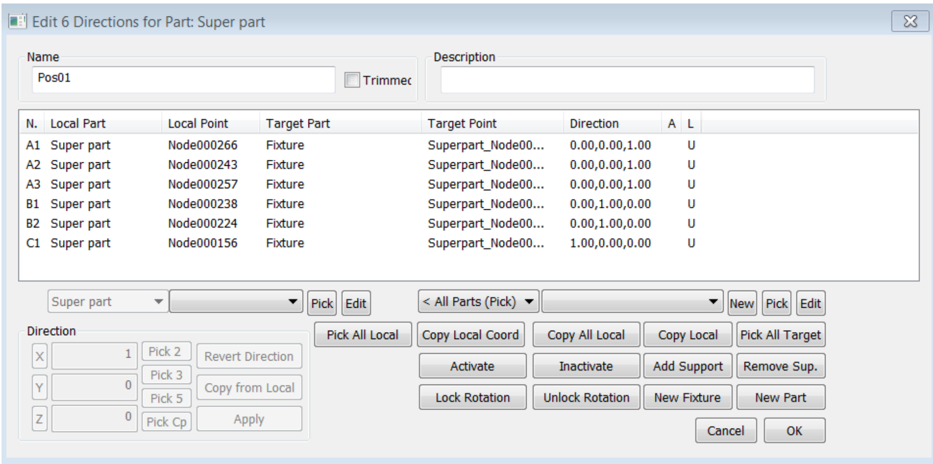


Figure 32. Positioning between parent part and fixture

4. A subassembly was created containing the Super part and the fixture. To establish a sub assembly, the parts to be included should be selected under “Included parts”, see Figure 33. The component in the sub-assembly that does not generate movement should be selected as local ground (Software Manual, 2015). The local ground in this case was the fixture.

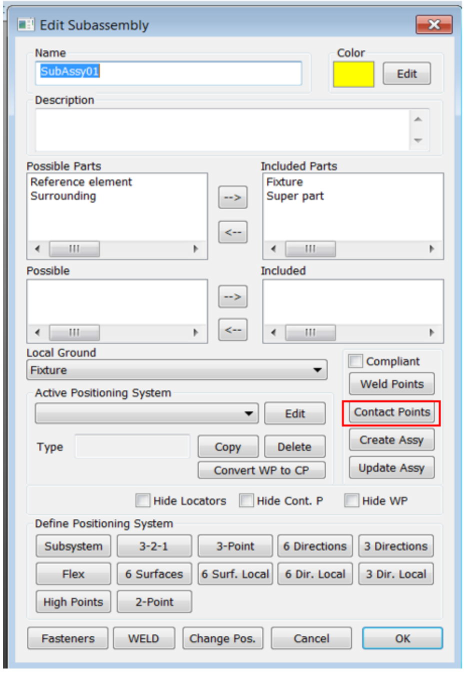


Figure 33. Subassembly

5. When a subassembly has been created, it is possible to create contact points. Contact points were created where the cut out in the door was assembled against the reference elements, see Figure 34.

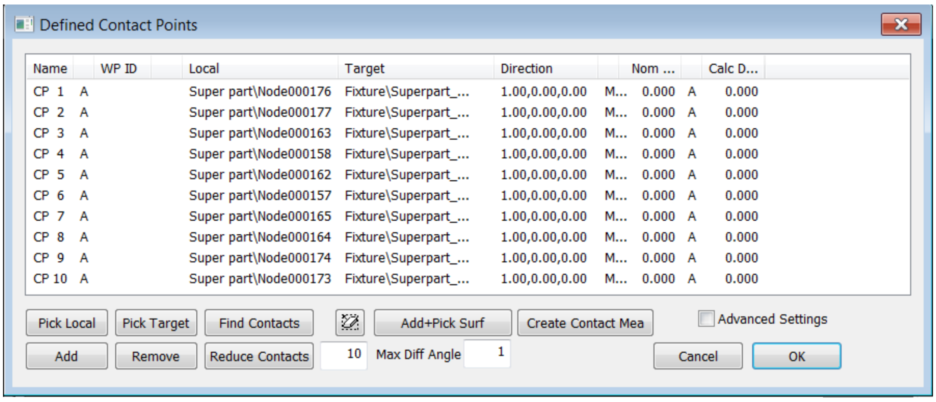


Figure 34. Contact points, local and target nodes

6. A tolerance was created in the positioning point in x-direction, see Figure 35. This enabled using the offset of the tolerance as input of the deviations attained from the physical study.

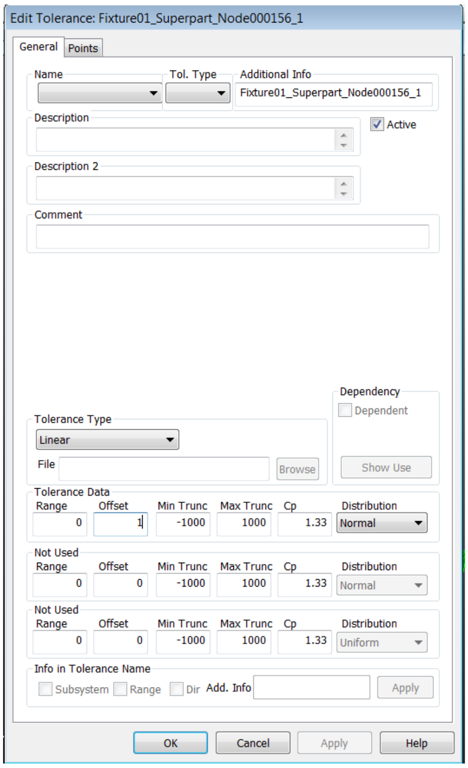


Figure 35. Tolerance

7. Measurements of the force in the contact points were created, see Figure 36. The contact forces revealed the force needed to gain the deviations which had been set as input. The force of interest was the force that needed to be induced by the operator, not the contact forces, but this is not possible in RD&T. By assuming force equilibrium of the component, it was possible to learn the force required from the operator by summing all the contact forces.

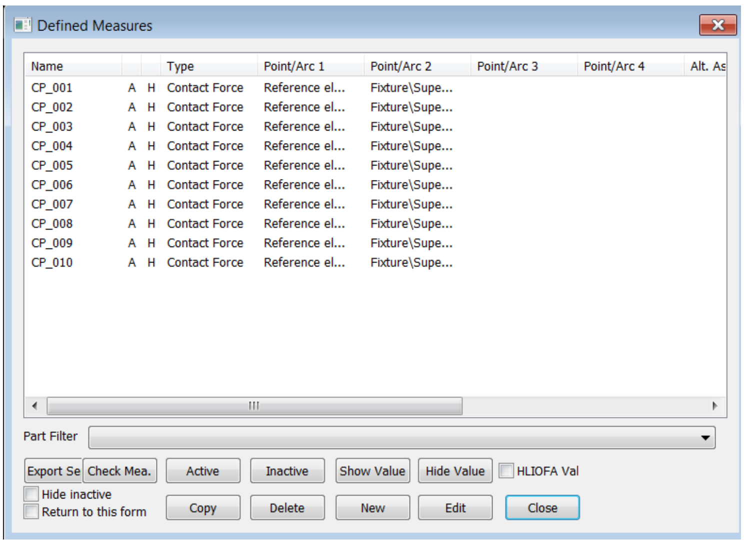


Figure 36. Contact force measurements

8. The variation simulation was performed and the results were visualised.

3.4 Manual assemblies vs. quality

To learn whether the assemblies performed in this project are in themselves contributing to poor quality, an assessment based on the 16 criteria for high manual assembly complexity was performed, view Appendix B. The assessment was performed for the assemblies related to car model A and B.

4. Results

This section will present the results of the master thesis project. First off, the results from the physical study will be presented, aiming at illustrating the deviations measured from the articles' nominal position after manual assemblies. The part variation for each article will also be presented to learn whether the variation measured during the assembly actually stems from the assemblies alone or not. This will be followed by a presentation of the results generated during the virtual study and a comparison of the physical and the virtual study is then possible. Then, a comparison of the conceptual differences of the articles will be performed at car model level. At last, the results of the assembly complexity assessment will be presented.

4.1 Physical study

During the physical study the placement of the seals were measured after every assembly. The results gained from the measures will be presented at article level (GRS, OWS) and car model level (A, B). The deviation from the nominal position of the GRS during repeated assembly is illustrated in Figure 37. The x-axis represents the number of assemblies and the y-axis represents the deviation. The chart indicates a substantial spread of the placement of GRS_A. The position of GRS_B also varies, but not the same extent. Unfortunately, the articles belonging to car model B were damaged during transportation from the supplier, which makes it difficult to proceed with the comparison of this result. Therefore, the results connected to GRS_B will not be considered further.

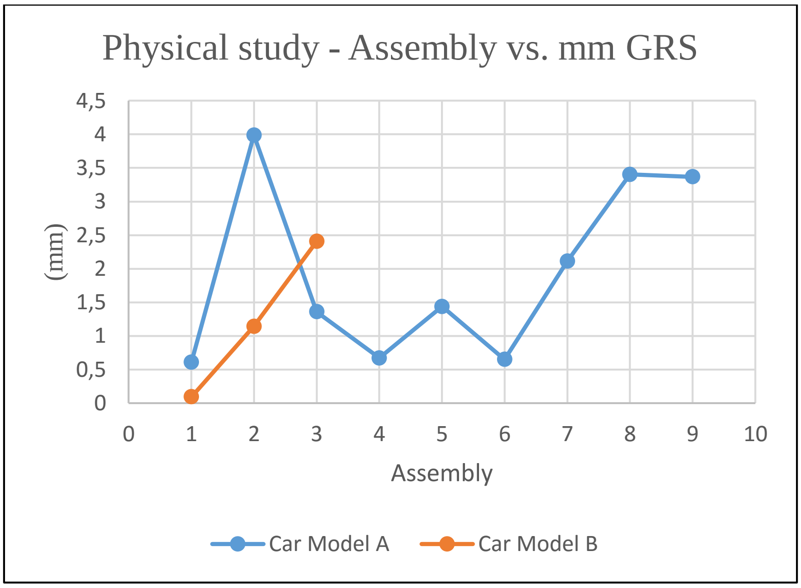


Figure 37. Deviation from the nominal position of the GRS

The same comparison for the OWS is illustrated in Figure 38. Since the Outer Waist Seals were transported together with the Glass Run Seals there is a possibility that they were damaged as well, even though this was not visually identifiable. The chart below indicates that the spread of the placement of OWS_A differs largely compared to OWS_B B. The underlying cause of the great spread for OWS_A is mainly due to the weak reference element of the component. The young's modulus of the reference element attached to the GRS and OWS is much lower for car model A compared to car model B. A low young's modulus can generate deformation of the reference elements, creating greater spread of the placement of the articles. Having such an unstable reference element can create an output that is operator dependant since the amount of deformation is dependent on the characteristics of the operator.

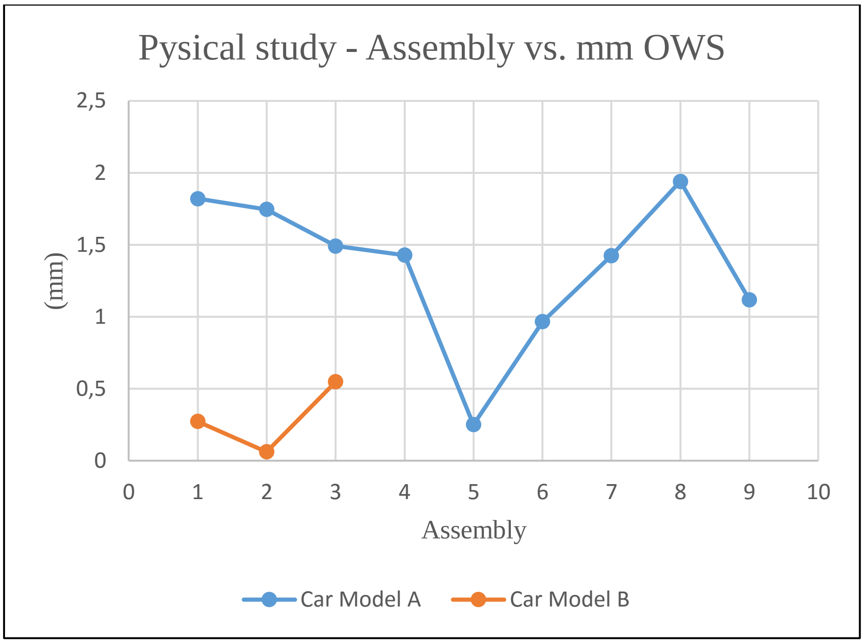


Figure 38. Deviation from the nominal position of the OWS

To learn whether or not part variation contributed to the variation presented above, an assessment of this was made by measuring each component repeatedly. The distances presented at the y-axis in the following charts is the distance between the reference element and the placement of the force during the assemblies. The results were gained by calculating the average distance for each article after repeating the measuring process six times for each article. Then, the average among all articles was calculated followed by plotting each individual mean in relation to the total average. In Figure 39, the part variation gained by measuring the samples of GRS_A is presented. The chart indicates that the part variation does not affect the deviations measured during the assembly to any greater extent.

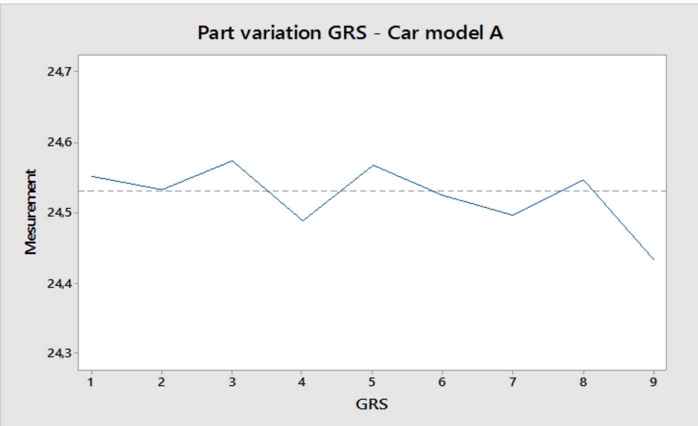


Figure 39. Part deviation of GRS_A

In Figure 40 the same trend is shown for the samples of OWS_A

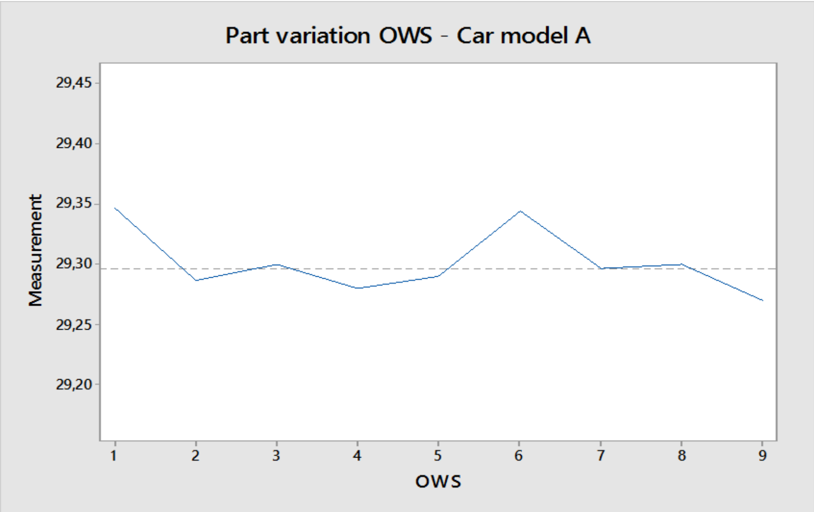


Figure 40. Part deviation of OWS_A

For the samples of OWS_B the results shows somewhat higher part variation, see Figure 41. This could be explained by the fact that the transportation of the components was not ideal and could have contributed to the results in this study.

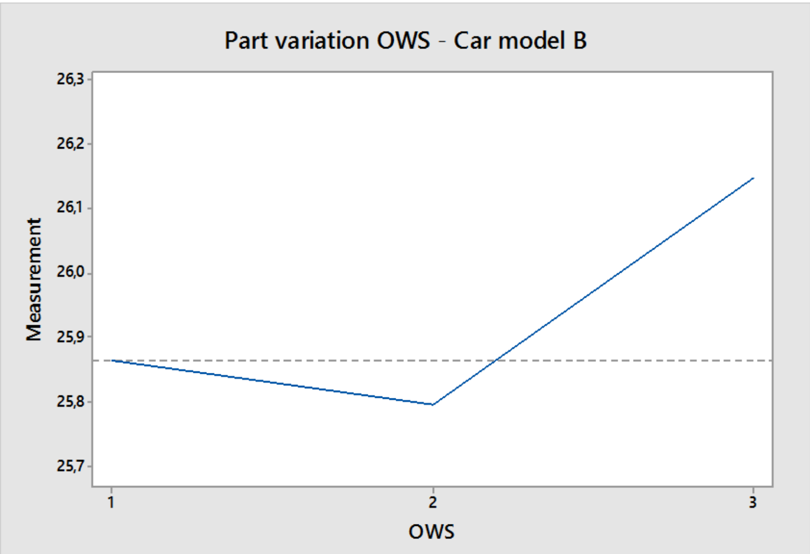


Figure 41. Part deviation of OWS_B

In addition to the measurements above, the force was also measured during the study. The result of the test evaluating the method to measure force can be seen in Figure 42. The reference value during the test was 45 N and the chart reveals that the force estimation used during the physical study is not an adequate method to measure force. The spread documented for each individual is large, as well as the deviation from the target value.

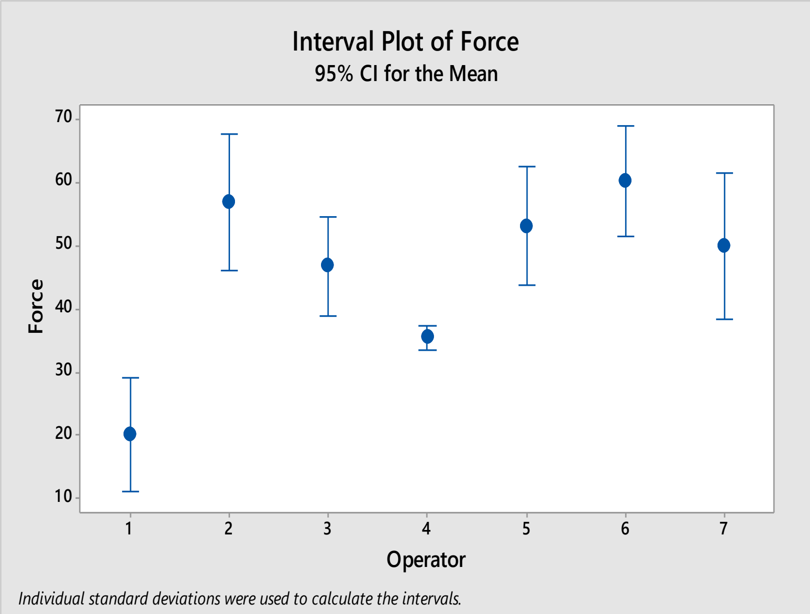


Figure 42. Insecurity of force estimation

4.2 Virtual study

The virtual study included creation of CAD models, meshing and modelling in RD&T. The deviation measured during the physical study was used as input in the RD&T models created for each article in order to study the forces generated virtually. The CAD models only illustrate the area of interest of the articles, namely the reference element for each article along with its closest surrounding, view Appendix F-H. Thereby, the RD&T models for every article included two parts, the reference element and its enclosing environment. The meshed models can be viewed in Appendix I-K.

In Figure 43 the reference element and the surrounding area of GRS_A is shown. The left image illustrates the RD&T model with the positioning system and contact points. To be able to illustrate the RD&T model clearly, the weld points are not visualized. The right picture illustrates the actual reference element of GRS_A and its surrounding.

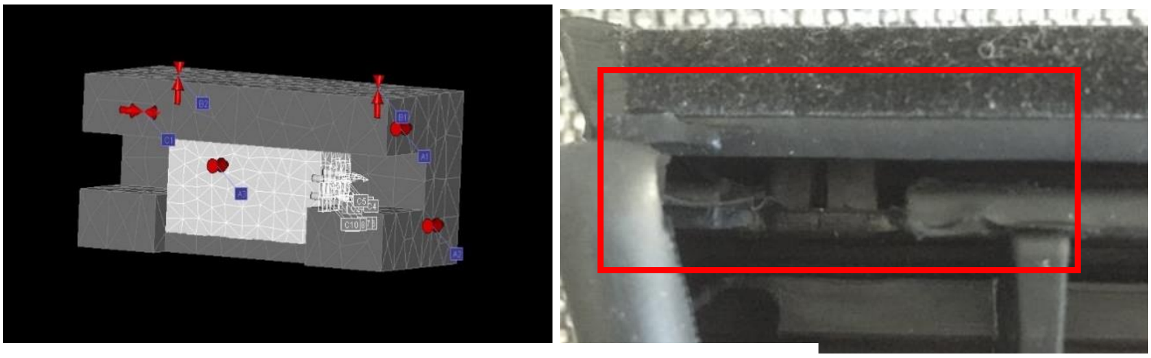


Figure 43. Reference element and surrounding GRS_A

The reference element of OWS_A has a different appearance compared to the GRS_A. In Figure 44 the RD&T model of OWS_A is illustrated along with the corresponding reference element at the actual seal.

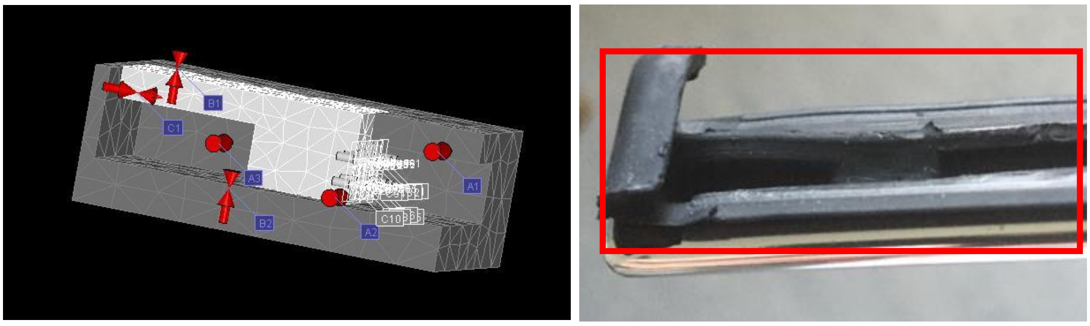


Figure 44. Reference element and surrounding OWS_A

The reference element of OWS_B is more rigid and its RD&T model and correspondance to the actual seal is shown in Figure 45.

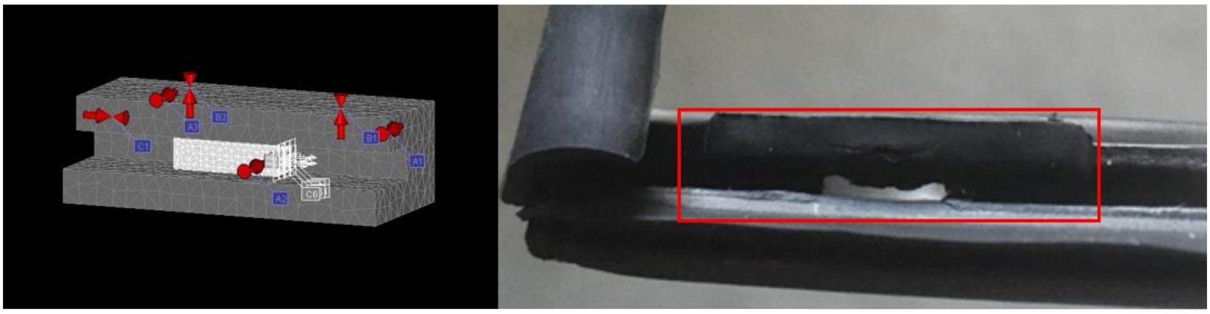


Figure 45. Reference element and surrounding OWS_B

When implementing the deviations in every separate RD&T model, the corresponding forces are generated. In Figure 46 the forces gained when implementing the deviations of the placement of the GRS_A and OWS_A in RD&T are illustrated. The chart clearly shows a linear trend between deviation and force. This indicates that the harder the operator push the greater the deviation, which confirms the intuitive relation between force and deviation. The linearity could be explained by the fact that RD&T cannot handle material with nonlinear young's modulus. In RD&T a constant figure of the young's modulus was used, which does not represent the actual behaviour of the material.

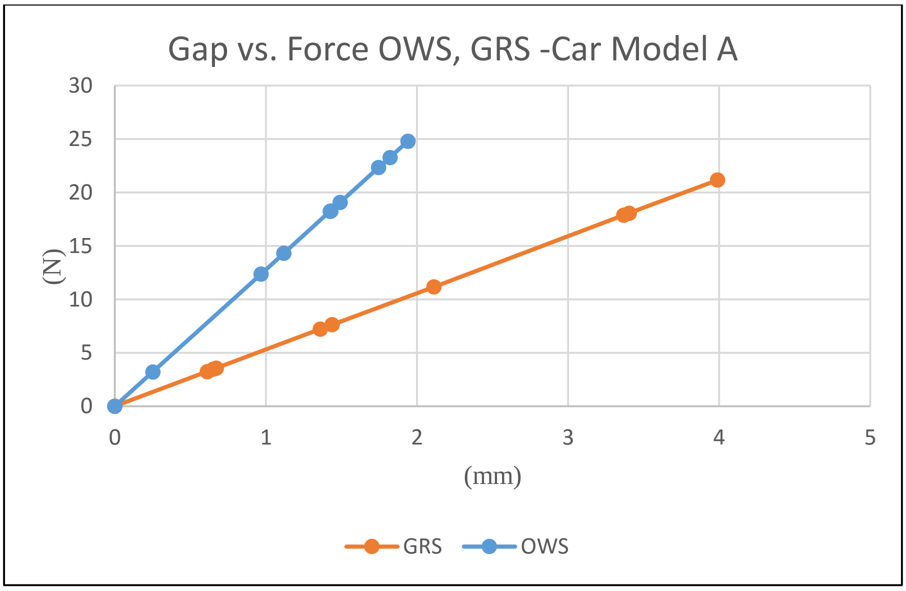


Figure 46. Output force from RD&T models belonging to car model A

The outcome generated when implementing the results from the physical study in the RD&T model representing OWS_B can be seen in Figure 47. The part variation is extracted in this case, since it was somewhat higher for OWS_B. The great force in the third measuring point can be caused by a backlash in the reference element. It seems reasonable that when the reference element is rigid, the influence of the force during assembly has less effect on the variation.

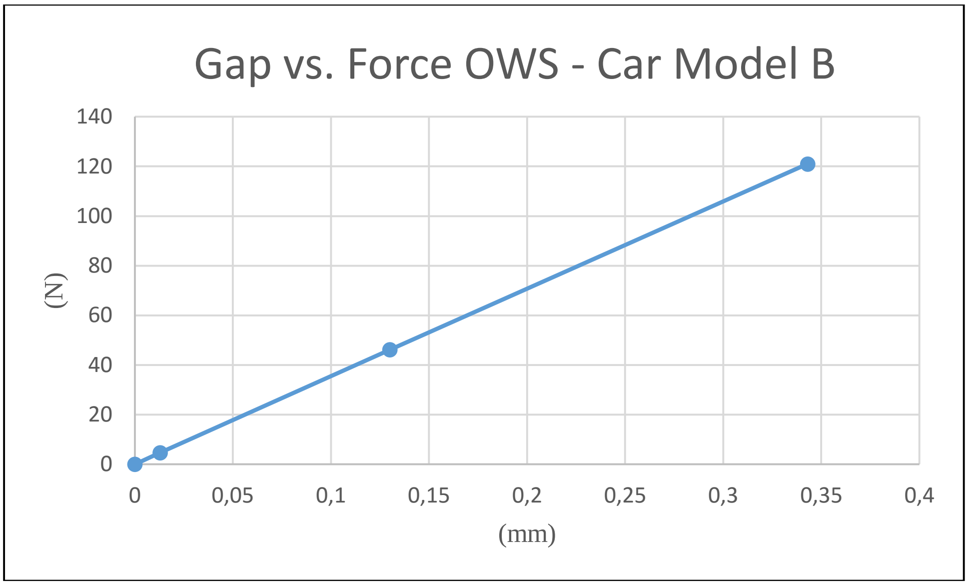


Figure 47. Output force from RD&T models belonging to car model B

4.3 Comparative study of physical and virtual study

Comparing the results from the physical and the virtual studies will indicate whether or not there is a relation between them. Due to the insecurity of the method used to measure force, it can be stated directly that there will be no clear correlation between the results from the physical and the virtual study. To compensate for this insecurity, the Root-Mean-Square method can be used to link the data of the force measurements. Since there are few measurements made and the insecurity is high, the correlation between the line generated by the RMS method and the actual data is questionable but it could be used to identify a trend.

In Figure 48 the relation between the physical and the virtual study is illustrated for GRS_A. The blue curve was presented in the previous section and illustrates the relation between force and deviation virtually. The orange curve illustrates the relation between force and deviation from the physical study and it illustrates the insecurity of the force measurements. Using the RMS method, the dotted orange line is created. First off, it is clear that when comparing the physical and the virtual results there is no correlation. Focusing on comparing RMS line and the virtual line, the slope of the lines are similar. This indicates that having a more precise method to measure force could have generated a correlation among the two. The forces attained during the physical study are higher compared to the corresponding forces virtually. One possible reason for this phenomena could be that the frictional force was not taken into consideration during the virtual study.

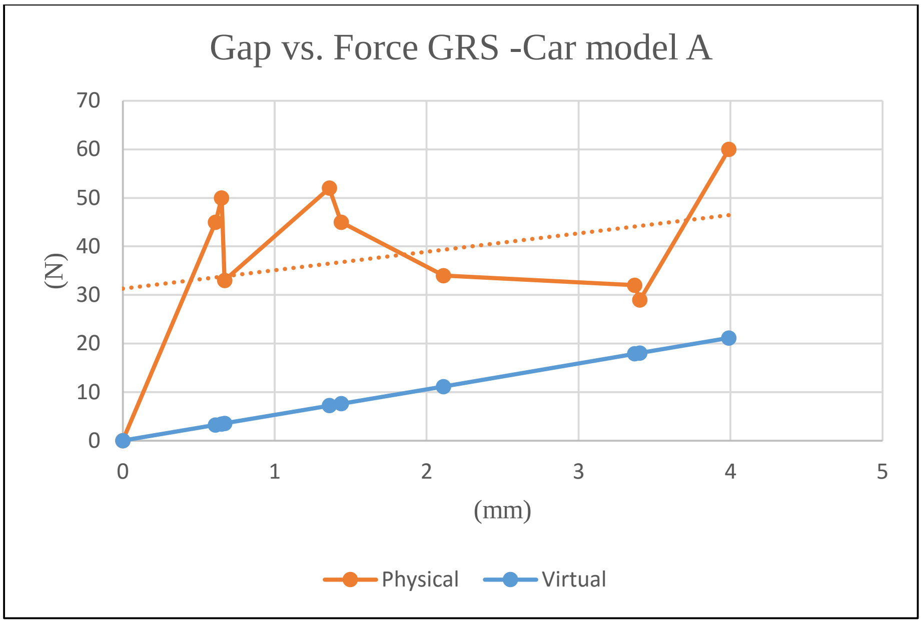


Figure 48. Comparison of physical and virtual results, GRS_A

In Figure 49 the corresponding result for the OWS_A is illustrated. The same trend as for GRS_A is shown in this case.

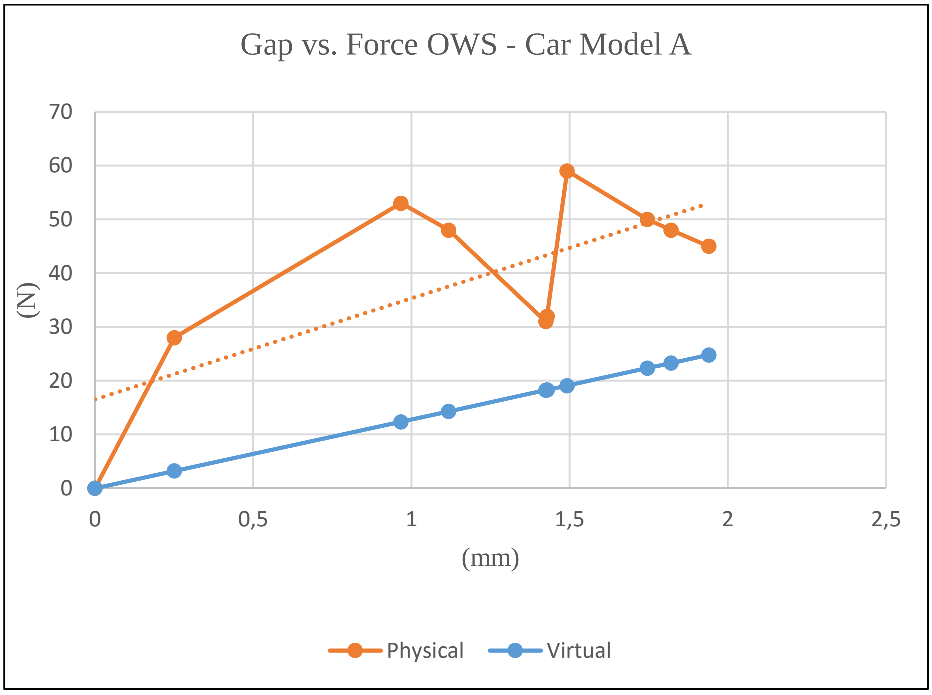


Figure 49. Comparison of physical and virtual results, OWS_A

Concerning the comparison of physical and virtual results regarding OWS_B the part variation was removed since it was somewhat higher for OWS_B. The large force generated in the third measuring point in Figure 50 can be, as mentioned previously, due to a backlash in the reference element.

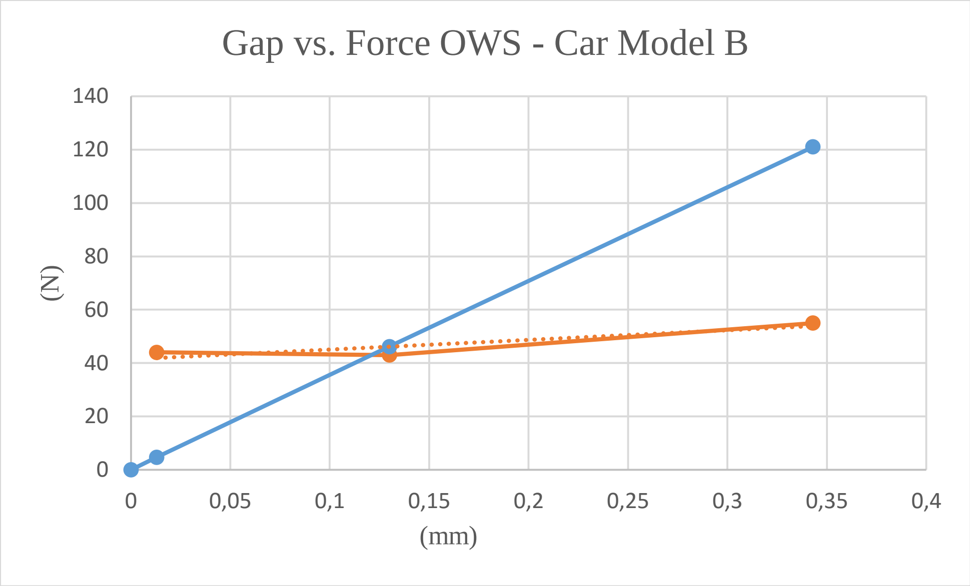


Figure 50. Comparison of physical and virtual results, OWS_B

4.4 Conceptual differences at car model level

When importing the deviations in RD&T it was possible to simulate the deformation of the reference elements. Due to the weak reference elements of GRS_A and OWS_A, deformation of the reference elements can be expected. The deformation generated by RD&T can be illustrated in Figure 51. This illustrates what happens when the weak reference element is pressed against the rigid rigid cut out of the door.

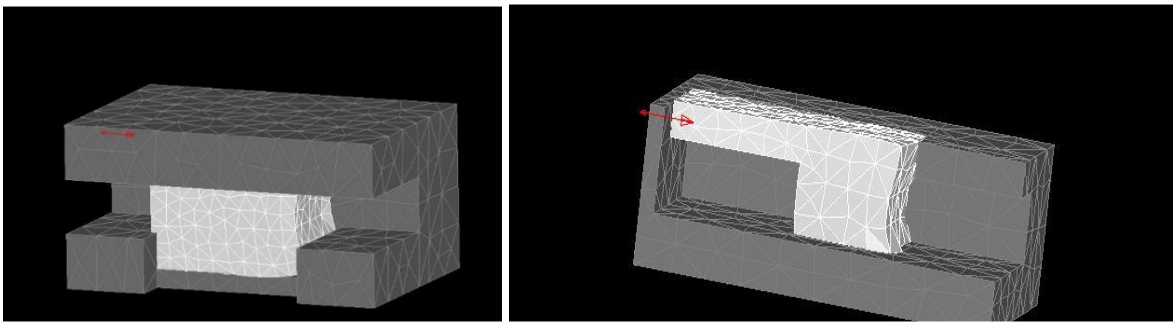


Figure 51. Left: Deformation of reference element of GRS_A. Right: Deformation of reference element of OWS_A

It could also be expected that the deformation of OWS_B is not as extensive as for the components shown above since the reference element is much more rigid. Figure 52 illustrates that the deformation of the reference element is very small, if even visible.

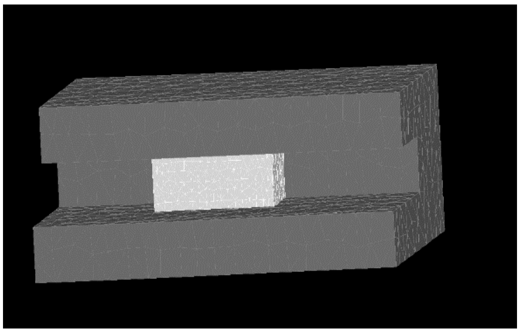


Figure 52. Deformation of reference element of OWS_B

The concept used for car model B regarding the reference element of the seals creates a relatively robust solution and the results clearly stresses the benefits of this concept. The concept for the components belonging to car model A can be severely questioned due to its sensitivity to variation.

4.5 Assembly complexity assessment

The “16 criteria for high manual assembly complexity (HC) considered as tricky and demanding operations” was used to evaluate whether the assemblies related to car model A and B can be considered as complex. This is of interest since complex assemblies can affect the quality of the product negatively. Each criteria has been evaluated for both car model A and B, see Figure 53.

16 criteria for high manual assembly complexity (HC)		
Criteria	**Car model A**	**Car model B**
1. Many different ways of doing the task	No	No
2. Many individual details and part operations	No	No
3. Time demanding operations	No	No
4. No clear mounting position of parts and components	Yes	Yes
5. Poor accessibility	No	No
6. Hidden operations	Yes	Yes
7. Poor ergonomic conditions implying risk of harmful impact on operators	No	No
8. Operator dependent operations requiring experience/knowledge to be properly done	Yes	No
9.Operations must be done in a certain order/sequence	Yes	Yes
10. Visual inspection of fitting and tolerances, i.e. careful subjective assessment of the quality results	Yes	Yes
11. Accuracy/precision demanding	Yes	Yes
12. Need of adjustment	Yes	Yes
13. Geometric environment has a lot of variation (tolerances), i.e. the level of fitting and adjustment vary between the products	No	No
14. Need clear work instructions	Yes	Yes
15. Soft and flexible material	Yes	No
16. Lack of (immediate) feedback of properly done work, e.g. a click sound and/or compliance with reference points	Yes	Yes
Result	**10**	**8**

Figure 53. 16 criteria for high manual assembly complexity (HC)

The result show that the assemblies can be considered as having a moderate degree of complexity, which could affect the quality negatively. An assembly is considered as having a moderate degree of complexity when the score of the test is in the range of 8-11. The problematic criteria's identified will be described further.

Criteria 6 – Hidden operations
Since the view is blocked when pressing the reference element of the articles against the cut out in the door the operations can be considered to be hidden.

Criteria 8 – Operator dependent operations requiring experience/knowledge to be properly done
An experienced operator is more likely to be able to place the reference elements correctly. Many experienced operators' are aware of the sensitivity stemming from the weak reference elements and have thereby learned ways to compensate for this. However, this is only the case for the components of car model A. For the components belonging to car model B, the experience does not matter as much since the reference elements are more robust.

Criteria 9 – Operations must be done in a certain order
The operations of attaching the seals to the car door always has to start by aligning the reference element against the cut out in the door. After this operation, the rest of the seal is assembled.

Criteria 10 – Visual inspection of fitting and tolerances, i.e. careful subjective assessment of the quality results
When having assembled the seal the operator checks that the chrome strip is properly aligned. This allow subjectivity, which could generate varying outcome.

Criteria 11 – Accuracy/precision demanding
The fitting between the reference element and the cut out in the door require precision in order to attach the seal correctly. Since the reference element is very small, it hampers precision.

Criteria 12 – Need of adjustment
Due to the obvious problems with the assembly of these components there is a clear need of adjustment after the assembly.

Criteria 14 – Need clear work instructions
It is of great importance that the operator know how to assemble the reference element since this affect the final position of the component. Therefore, clear work instructions are needed that describe the process in detail.

Criteria 15 – Soft and flexible material
The reference element of GRS_A and OWS_A is soft and flexible, but this is not the case for GRS_B and OWS_B.

Criteria 16 – Lack of (immediate) feedback of properly done work, e.g. a click sound and/or compliance with reference points
When or if the operator complies with the reference points there is no feedback given to the operator, leaving them unaware of the actual placement of the component.

5. Discussion

The master's thesis indicate that there is no evident correlation between the virtual and the physical tests performed in this project. However, using the RMS method there are implications of a matching trend between the virtual and the physical tests. When studying the comparative results of this trend, it is clear that the slope from the virtual tests and the RMS slope coincides. The magnitude of them, however, differs. This could be explained by, as mentioned in the result, that the frictional force was not taken into consideration in the virtual study. Since the correlation between the line generated by the RMS method and the actual data from the physical study is questionable there are still uncertainties regarding the identified matching trend. Therefore, there are several aspects that need to be further discussed that could have affected the result attained during this project.

5.1 Cross functional aspects

This project has pinpointed the importance of being able to take operator influence during manual assemblies into consideration in the geometry assurance process. Competitiveness can be negatively affected if this is not done, since small geometrical errors in early phases of development can lead to severe consequences downstream (Chang and Gossard, 1997). To overcome this, using a concept that is sensitive with respect to assembly variation, would require tight tolerances which would generate high expenditures (Söderberg and Lindkvist, 1999). Due to the tough competition in the automotive industry today, this would lead to a snowball effect generating low quality (both functionally and aesthetically), long lead times and high cost. Customer satisfaction would not be met, risking setbacks for the manufacturer. Therefore, it is of great importance to create robust designs.

This project aimed to contribute to the process of making assembly variation acknowledged in early phases of development. The approach used in this project was evaluated in that purpose and obstacles using this approach have incurred. Hence, the human factor and the human movements are not easily translatable when entering the virtual world, nor is it simple to perform physical tests and create reliable ways to measure without including noise. The project has also identified an example of a disparity among concept developers and the assembly process. It is one thing to determine positioning points virtually, and optimizing them based on only one perspective. However, it is a completely different task when wanting to create a positioning system that is not only successful virtually. The linkage among physical and virtual work is lost when the optimizations made in early phases do not accommodate to what is practicable. It does not matter how well a positioning system works virtually if it is nearly impossible for the operator to perform the positioning correctly. According to Rosenqvist *et.al.* (2013) assemblies where the positioning points are hidden can cause this problem. The reference elements of car model A are great examples of this. The results clearly indicate a substantial spread of the position of GRS_A and OWS_A. Working virtually, it is easy to forget what impact material selection of reference elements can have on the geometrical variation of the final product. In the virtual software the type of material is not visually portrayed, which could contribute to making people less likely to react. Intuitively, one would realize that a reference element similar to rubber is likely to cause problems. Therefore, it is of great importance to make a concept robust regarding assembly in early phases of development and doing so requires an integrated way of working where the assembly variation is considered in parallel to part variation.

During this project, the difficulties of performing physical tests and correlating the results with simulations have been evident. The project has required fluctuating between two different worlds, the physical and the virtual. During the project, support have been given by people working solely in the practical field and by people that are mainly focusing on theoretical aspects. Sometimes the advice from the two perspectives have been opposing, making it a part of this master's thesis to create a linkage between them. Working with people from different departments means working with personnel with varying perspectives. Being a middle hand between different departments can be demanding since it requires a lot of discussions to reach an understanding. To take a stand based on two different sources of information can be difficult and it is not always easy to foresee the obstacles to come. An illustrating example can be the direction of force in the physical and the virtual study. In the physical study, which was performed before the virtual study, the force was directed with a 45 degree angle against the GRS and the OWS. Meanwhile, when performing the virtual study it was not possible to simulate this and the deviations were set horizontally. Simplifications had to be made to make the comparison possible, which could have affected the accuracy of the result. This can, in one perspective, be viewed as a troublesome simplification but in another perspective it can be taken lightly with the attitude that adjustments between physical movements often have to be adjusted when implemented virtually.

5.2 Reliability of physical study

The CMM measures with high accuracy and it is controlled regularly. In contrast to the measurements generated by the CMM, the method to measure force is questionable. To measure a parameter in retrospect is an insecure method since it is based on an impression and it is difficult to recreate the accurate value. One could question that the method was used when the evaluation of the force assessment showed large spread and low accuracy. The force assessment revealed that when the target value was 45 N the spread for each individual in some cases measured up to 20 N. If the spread of the measurements can be approximately half of the magnitude of the target value, it is difficult to generate reliable results. The decision to use this method was due to scarce resources. There are force transducers available at the market, which could have increased the accuracy of the force measurements by being able to measure force during ongoing assembly.

The reason for selecting three operators was to evaluate how the result differed among varying operators. It was of interest to investigate whether it was possible to detect different patterns depending on different characteristics of the operators. This comparison was unfortunately not possible due to a measurement error detected after the physical study.

5.3 Part variation vs. variation due to disassembly

Another aspect that is important to mention is the number of observations made. Due to restrictions of material, the number of assemblies were limited. During the tests of car model A, nine repetitions were possible but only three repetitions were possible when studying car model B. It is of course difficult to make extensive conclusions based on such a limited number of observations.

One crossroad during the project regarded this issue and it concerned whether or not the components should be reused after they had been assembled once or if they should be discarded after one assembly. The latter was chosen, as described above, meaning that the noise to consider in the study concerned part variation. Part variation occurs when the nominal form of components are not reached in manufacturing (Chang and Gossard, 1997). If the material would have been reused, part variation could have been excluded since the same parts would have been used repeatedly. The other option was, as mentioned, to assemble each article more than one time. Doing so would on the other hand risk documenting deviations stemming from the geometrical variation caused by the fact that the articles are very likely to be damaged during disassembly. During the physical study it was evident that it would not have been possible to reuse the articles since many of them were severely damaged during disassembly. Best case would have been if the articles did not break during disassembly, since this would have made it possible to eliminate both part variation and the variation caused by the disassembly.

5.4 Reliability of virtual study

The initial idea was to use the CAD models created by VCC of complete articles but due to limitations of being able to mesh these articles, this was not possible. Since the reference elements and its closest surrounding were of interest during this project, the CAD models created to perform the virtual tests only portrayed this limited area of the product. This assumption is valid since this part of the article guides the position of the entire article. Regarding the process of meshing, a smaller element size will generate a more accurate result. Smaller element size also creates big files, which can be troublesome when importing the mesh in RD&T. The element size was therefore limited by the capacity of RD&T. Since the elements creates the possibility of observing the approximate behaviour of the article (Ottosen and Petersson, 1992), fewer elements would reasonably generate lower accuracy when studying the behaviour virtually.

RD&T made it possible to analyse the result from the physical study virtually, but the software is not typically used to perform the type of simulations made during this project. Since it is not possible to apply a force to attain the resulting deviation, the virtual study was performed conversely in comparison to the physical study. This means that if a correlation would have been detected during this project, the software does not yet eliminate the usage physical tests since the deviations had to be known before the virtual study. If it was possible to import forces in RD&T, it would have been possible to eliminate physical tests assuming that there would have been a correlation.

As mentioned in the section describing the methodology, the virtual assessment was performed by importing deviations in a positioning point to then be able to generate the forces required to reach the deviation that had been imported. The force generated during simulation was the contact force occurring between the reference element and the cut out of the door, not the actual force occurring in the positioning point. Assuming force equilibrium of the components, it was estimated that these two forces were equal. The deviations were imported via the offset of a tolerance that was created in the positioning point, meaning that there is no developed method to insert actual deviations in the program. To clarify, in the virtual study many functions were used that are not developed in this purpose. Ideally it would have been possible to apply a force in optional direction, perform the simulation and afterwards be able to learn what deviations had been generated by the force that had been applied. Many additional functions have been made to the software recently, which is continuously developing, and the possibility to measure force has not been available for long. As the software keeps developing, it creates improved conditions to perform these types of studies.

Another source of error can be the fact that the software is not able to handle material with a varying young's modulus. This made the relation between force and deviation linear, which might not be the case.

To use weld points to simulate that the surrounding area and the reference element are attached is also an approximation since they are not welded in reality. The number of contact points used to simulate the conflict between the reference element and the door is also limited by the number of nodal points located on the reference element, which also could contribute to differences among the physical and the virtual results.

5.5 Difficulties of practical activities during a master's thesis project

In retrospect, it would have been appropriate to assess the main obstacles that could occur when performing practical tests before the project started. When performing physical tests, the result of the project is dependant of the resources allocated and it is difficult to influence the resources given. In physical tests it is also difficult to exclude noise factors. When measuring how much a parameter is deviating, it is of great importance not to include irrelevant factors contributing to the deviation. It is challenging to know whether a parameter has been successfully isolated or not.

During the physical study the factors that could affect the result were part variation, assembly variation and variation of the position of the door. Since assembly variation was the desired parameter, the other two had to be eliminated. Part variation was considered, as stated in the result, and it showed that it affected the result to a small extent. The position of the door was controlled by the CMM using reference points at the door. The difficulties lies in quantifying the impact of these parameters to extract the desired result. This obstacle is nearly impossible to overcome during a master's thesis and most likely requires more resource in terms of time, knowledge and material.

5.6 Integrated concept

The main task of seals are to keep two environments separate. In this case, the task of the GRS and the OWS is to prohibit water from entering the interior of the car and rubber is a common material used. The concept of all seals included in this study is structured flowingly; the outermost material is the chrome strip fixed to the seal. The next layer is the actual sealing material, rubber. The adjacent material is plastic, which is the base for the reference element consisting of yet another material, see Figure 54.

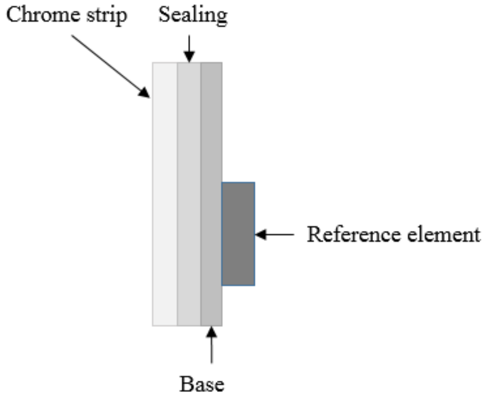


Figure 54. Construction of articles

There is no clear reason to why the base of the reference element and the reference element itself is constructed as two components. This is the case for both car model A and car model B. For car model A, the base is much more rigid compared to its weak reference element. Regarding car model B, the base and the reference element are similar with regards to rigidness. A suggestion of improvement of the concept would be to integrate the base and the reference element, reducing the number of ingoing materials. This could enable a simplified concept, and also improve the robustness of the reference element. This concept would also be easier to evaluate in RD&T since it would eliminate the step of creating weld points since the two parts now are joined as one from the start. A suggestion of improvement could look like in Figure 55. The concept only contains one part, compared to current concepts. This would eliminate the wear occurring in the interface between the two different materials in today's concept.

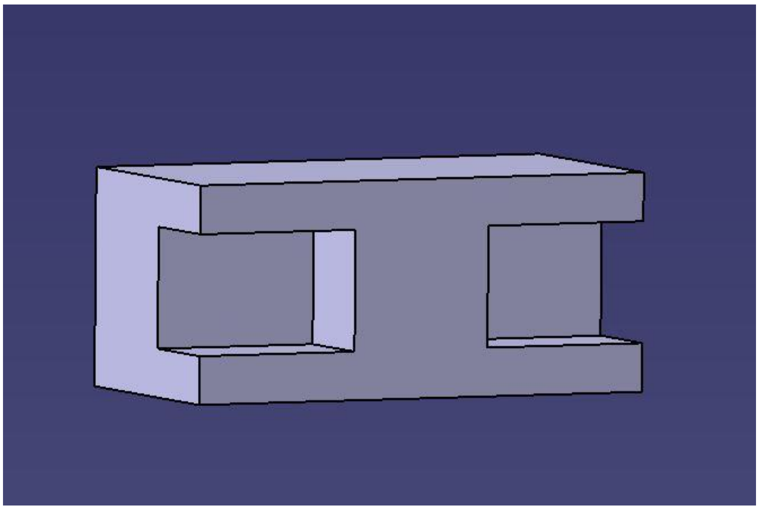


Figure 55. CAD model of integrated concept

Selecting a material with high young's modulus for the entire component, as for the reference element of car model B, the concept would be more robust. By meshing the CAD model it can then be imported as a compliant part in RD&T. By inserting a deviation that frequently occurred during the physical study, e.g. 1 mm, the contact forces can indicate whether the deviation is likely to occur. In Figure 56, the RD&T model of the integrated concept is illustrated. When the deviation of 1 mm was imported in the model, the contact forces revealed that in order for the position to differ 1 mm from its nominal position, the operator had to reach 1878 N, which is impossible. This indicates that the solution is insensitive to assembly variation. It also indicates that *if* this type of deviation could be measured the variation would not stem from the amount of force induced by the operator. It would most likely have to do with part variation.

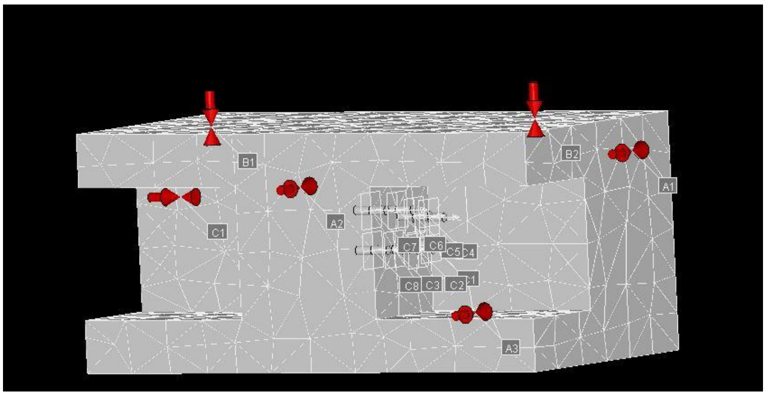


Figure 56. RD&T model of integrated concept

5.7 Assembly complexity

The assembly complexity assessment revealed that the assemblies studied during this project can be considered having a moderate degree of complexity, which could affect the quality negatively. The suggestion of improvement does not improve the fact that the assembly includes hidden operations, that the accuracy is demanding or that there is no feedback given to the operator when the reference element is placed correctly. On the other hand, the suggestion eliminates the importance of having an experienced operator since force in this concept is an irrelevant parameter. The concept also eliminates the usage of soft material, which reduces the complexity of the assembly. To interconnect this reasoning with the relation between the physical and the virtual results, it would probably have been easier to perform the virtual simulation using this concept. Using a rigid material, the young’s modulus can be considered as constant which would have improved the accuracy of the results from RD&T. The number of steps performed in RD&T would have been fewer since the parent part is not needed. It is likely to assume that a complex assembly process is more difficult to test virtually compared to an assembly with low complexity.

6. Conclusion

In this section the research questions will be concisely answered. The research questions regarded if it is possible to quantify operator related variation in manual assemblies, whether it is possible to detect a correlation between virtual simulations of manual assemblies and actual manual assemblies and it if a virtual software can be used to predict the robustness of a design concept with regards to manual assemblies.

6.1 Quantification of variation in manual assemblies

The master's thesis project concludes that it is possible to quantify variation in manual assemblies. The variation measured during the physical tests revealed that although the same operator is assembling repeatedly, the position of the article assembled will differ. The fact that the components with a rigid reference element generated less spread compared to the articles with a weak reference element also indicates that the quantification of the variation from the manual assemblies are accurate. Due to difficulties of isolating parameters contributing to the variation, the values attained could to a small extent be influenced by other factors.

6.2 Correlation between physical and virtual results

There is no correlation between the virtual and the physical tests performed, mainly due to the method to measure force. An additional factor contributing to the low correlation is that RD&T is not fully equipped to handle the type of simulation performed, as discussed. Improving the test methods used and developing RD&T for this purpose could enable a correlation.

6.3 Virtual evaluation of robustness of design concept

The simulations in RD&T enabled evaluation of the design concepts and it can be concluded that it is possible to evaluate the robustness of a design concept virtually. The simulation of $\mathrm{GRS_A}$ and $\mathrm{OWS_A}$ showed that they deform greatly during the assemblies and the simulation of $\mathrm{OWS_B}$ illustrated that a rigid reference element will not deform to the same extent. Since the reference elements are hidden during the assembly, it was not possible to visually see this deformation during the physical study but the variation attained indicates that large deformations emerge when assembling $\mathrm{GRS_A}$ and $\mathrm{OWS_A}$. It can also be concluded that the variation can be amplified by the fact that the assembly processes studied can be regarded as having a moderate degree of complexity.

7. Future research

This master's thesis has only scratched the surface of the work that lies ahead to be able to quantify operators' contribution to variation during manual assemblies in the concept phase. A lot more research and tests need to be made before it is possible to enable a way of working where the predictions of variation are reliable enough to eliminate the need of prototypes or physical tests. To be able to quantify operators' contribution to variation during manual assemblies virtually, there are several aspects that need to be considered.

One recommendation for further research concerns performing the same study with a different approach of measuring force. By establishing a method to measure force that enables the measurement process to be done during ongoing assembly could lead to detecting a correlation between the physical and the virtual results. This should be done in addition to increasing the number of observations, to generate increased reliability of the results.

Regarding the virtual test methods, more research should be put into evaluating what software to use when evaluating manual assemblies. RD&T is an appropriate software to use if continuous development of the compliance module is achieved, making it possible to induce forces.

More effort should, in future research, be put into isolating the parameter of interest and the behaviour of rubber also needs to be further investigated. In this project it was possible to evaluate the design concept virtually based on visual results. Future research could concern the possibility of quantifying the deformation that was visualised.

8. References

8.1 Articles

Agapiou, J. S., & Du, H. (2007). Assuring the day-to-day accuracy of coordinate measuring machines—a comparison of tools and procedures. *Journal of Manufacturing Processes*, *9*(2), 109-120.

Cai, N., Qiao, L., & Anwer, N. (2015). Assembly Model Representation for Variation Analysis. *Procedia CIRP, 27, 241-246.*

Camelio, J., Hu, S. J., & Ceglarek, D. (2003). Modeling variation propagation of multi-station assembly systems with compliant parts. *Journal of Mechanical Design, 125(4), 673-681*.

Chang, M., & Gossard, D. C. (1997). Modelling the assembly of compliant, non-ideal parts. *Computer-Aided Design, 29(10), 701-708.*

Falck, A-C., Rosenqvist, M., Lindkvist, L. & Söderberg, R. (2014). Geometrical robustness analysis considering manual assembly complexity. *Procedia CIRP, 23, 98-103*

Forslund, K., Wagersten, O., Tafuri, S., Segerdahl, D., Carlsson, J. S., Lindkvist, L., & Söderberg, R. (2011). Parameters Influencing the Perception of Geometrical Deviations in a Virtual Environment. *In ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (pp. 1105-1114). American Society of Mechanical Engineers.*

Rosenqvist, M., Örtengren, R. & Falck, A-C. (2014). Assembly failures and action cost in relation to complexity level and assembly ergonomics in manual assembly (part 2). *International Journal of Industrial Ergonomics, 44(3), 455-459.*

Rosenqvist, M., Falck, A-C., Wärmefjord, K. & 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 – November 13-21, San Diego, California, USA.*

Söderberg, R., Lindkvist, L., & Carlson, J. (2006). Virtual geometry assurance for effective product realization. *In First Nordic Conference on Product Lifecycle Management-NordPLM (Vol. 6, pp. 25-26).*

Söderberg, R., & Lindkvist, L. (1999). Computer aided assembly robustness evaluation. *Journal of Engineering Design, 10(2), 165-181.*

Söderberg, R. (1998). Robust design by support of CAT tools. *In Proceedings of the ASME Design Automation Conference, September 13-16, Atlanta, GA, USA DETC98/DAC-5633*

Söderberg, R., Wickman, C., & Lindkvist, L. (2008). Improving decision making by simulating and visualizing geometrical variation in non-rigid assemblies. *CIRP Annals-Manufacturing Technology, 57(1), 175-178.*

8.2 Books

Ottosen, N. & Petersson, H. (1992). Introduction to the FINITE ELEMENT METHOD. *University of Lund, Sweden.*

Lilja., Olsson. & Wickström. (2011). Ritteknik faktabok. *Produkt- och produktionsutveckling Chalmers Tekniska Högskola.*

8.3 Webpages

Directindustry. (2016). Innovalia metrology. Avaliable at: http://www.directindustry.com/prod/innovalia-metrology/product-161330-1655730.html#product-item_1655718 [Accessed May 1, 2016].

Globalspec. (2016). Engineering 360 Powered by IEEE GlobalSpec. Available at: http://www.globalspec.com/learnmore/manufacturing_process_equipment/inspection_tools_instruments/coordinate_measuring_machines_cmm [Accessed May 1, 2016].

RD&T Technology. (2016). The RD&T main steps to Geometrical Robustness. Available at: http://rdnt.se/steps.html. [Accessed May 5, 2016].

Software Manual. (2015). Robustness evaluation and tolerance analysis, RD&T.

VCC. (2015). Standard VCS 5060,6. Available from http://www.volvocars.net. [Accessed 2016-02-10].

Volvo Cars. (2016). Bygg din Volvo. Available from http://byggdinvolvo.volvocars.se/#/configurator?_ga=1.45144804.1913995781.1447683312. [Accessed 2016-05-16].

8.4 Interview

Johasson, Dag. (2016). Technical Expert at Robust Design and Tolerancing *Volvo Car Corporation.*

8.5 Lecture material

Lindkvist, L. (2016). Advanced Computer Aided Design: Geometry Assurance 1 Robust Design & Variation Simulation. *Chalmers University of Technology.*

9. Appendices

9.1 Appendix A: Gantt-Schedule

Planned activities	**Weeks**																				
	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Preparatory aspects																					
Access and applications	■	■																			
Master thesis description and outlines																					
Formulate research hypothesis	■	■																			
Establish time plan	■	■																			
Deliver planning report		■																			
Capability study																					
Specification of cases	■	■																			
Meeting with project initiator	■																				
Review method used	■	■	■	■																	
Repeat capability study																					
Contact relevant parties	■	■	■																		
Plan practical aspects		■	■	■																	
Execute					■	■	■														
Collect relevant data					■	■	■														
Analyze data								■	■												
Virtual correspondance																					
Contact relevant parties								■	■												
Introduction of virtual environment								■	■												
Analyze possibility of correlation										■	■	■									
Further direction of work procedure													■	■							
Documentation													■	■							
Final report											■	■	■	■	■	■	■	■	■	■	■
Literature study	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						
Presentation																					■
Opposition																				■	■
Update with supervisor at Chalmers				■				■				■				■				■	
Update with supervisor at Volvo	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

9.2 Appendix B: 16 criteria for high manual assembly complexity

16 criteria for high manual assembly complexity (HC) considered as “tricky and demanding” operations

1. Many different ways of doing the task
2. Many individual details and part operations
3. Time demanding operations
4. No clear mounting position of parts and components
5. Poor accessibility
6. Hidden operations
7. Poor ergonomic conditions implying risk of harmful impact on operators
8. Operator dependent operations requiring experience/knowledge to be properly done
9. Operations must be done in a certain order/sequence
10. Visual inspection of fitting and tolerances, i.e. careful subjective assessment of the quality results
11. Accuracy/precision demanding
12. Need of adjustment
13. Geometric environment has a lot of variation (tolerances), i.e. the level of fitting and adjustment vary between the products
14. Need clear work instructions
15. Soft and flexible material
16. Lack of (immediate) feedback of properly done work, e.g. a click sound and/or compliance with reference points

9.3 Appendix C: Scale of HC criteria

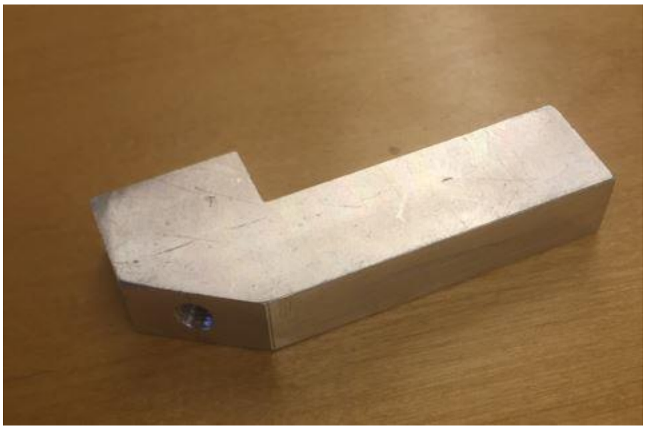
Scale for assessment of complexity level and fulfillment of high complexity (HC) criteria

Scale for assessment of complexity level and fulfillment of high complexity (HC) criteria.

Table 1
Scale for assessment of complexity level and fulfillment of high complexity (HC) criteria.

Complexity level	Degree of complexity	Fulfillment of 16 HC criteria
Green	Low	0–3 (0–19%)
Yellow-green	Rather low	4–7 (44-25%)
Yellow	Moderate	8–11 (50–69%)
Yellow-red	Rather high	12–14 (75–88%)
Red	High	15–16 (94–100%)

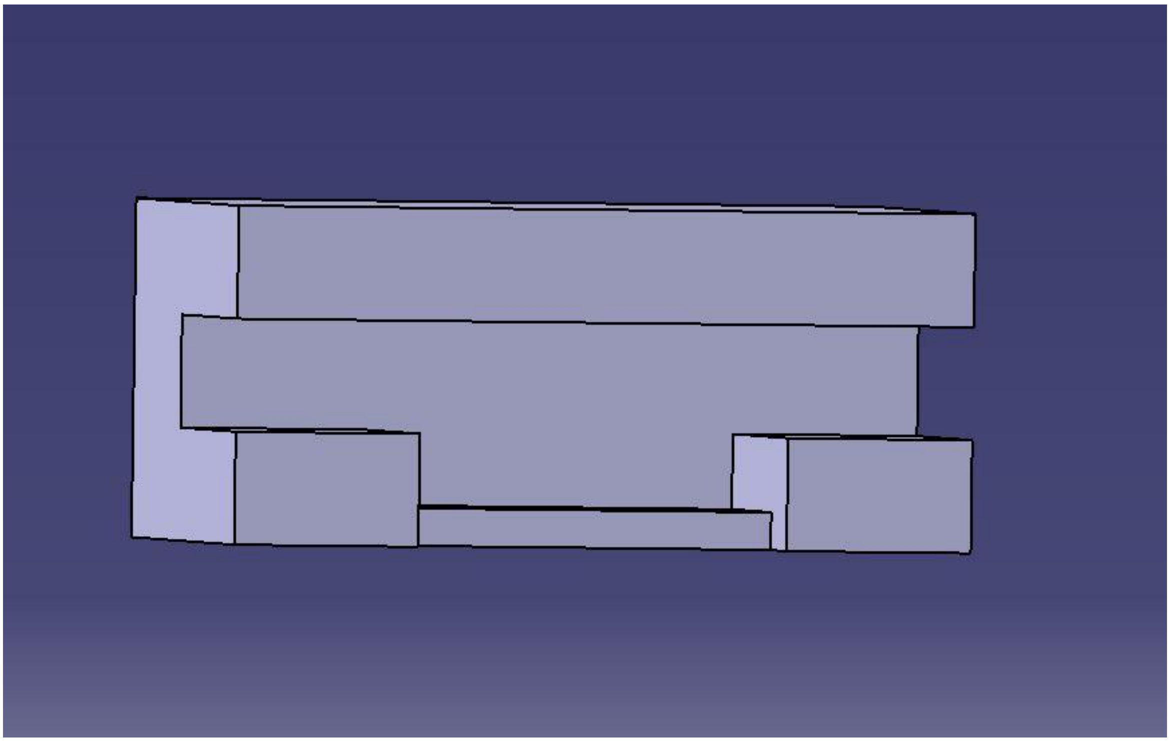
9.4 Appendix D: Pressure component GRS

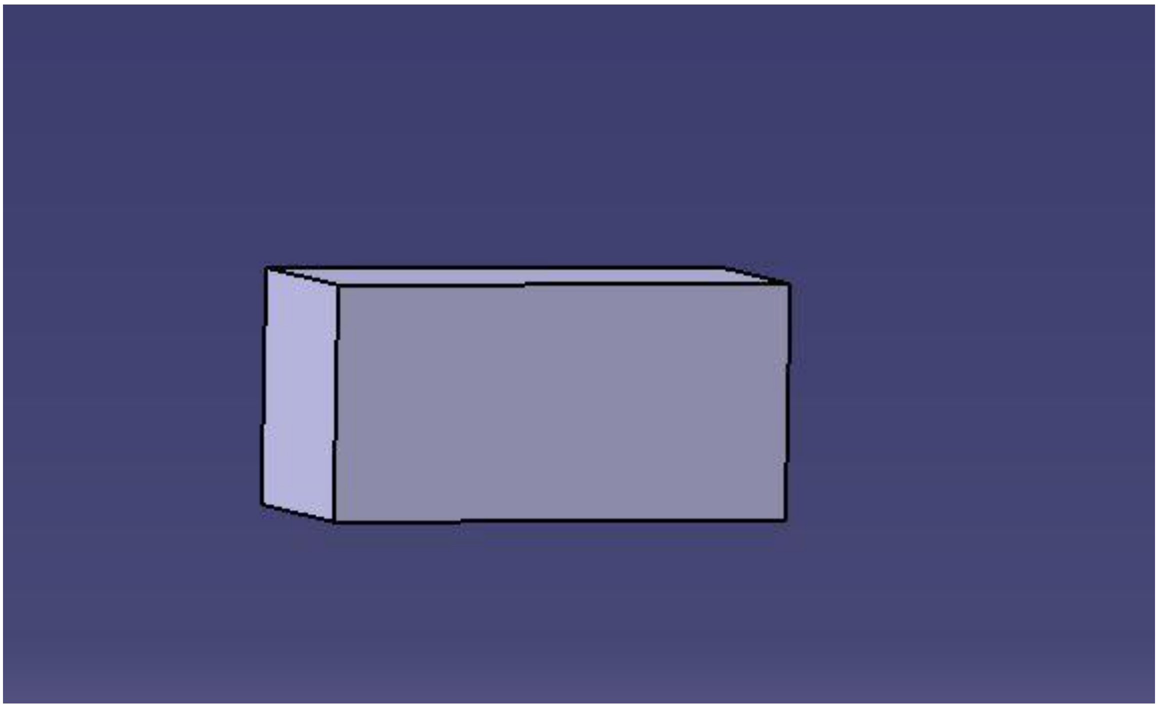


9.5 Appendix E: Pressure component OWS

9.6 Appendix F: CAD model GRS Car model A

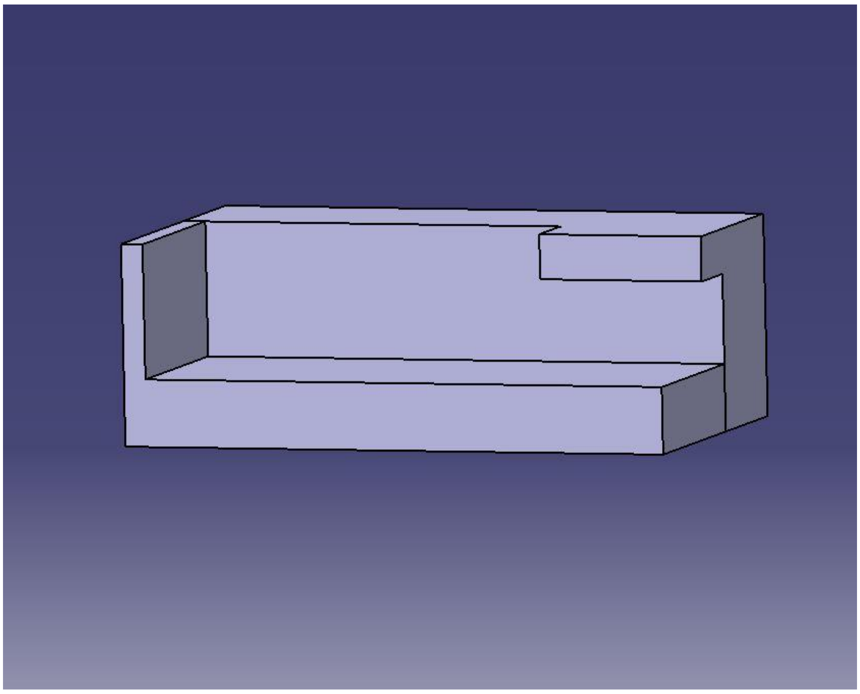
Car model A GRS – surrounding and reference element

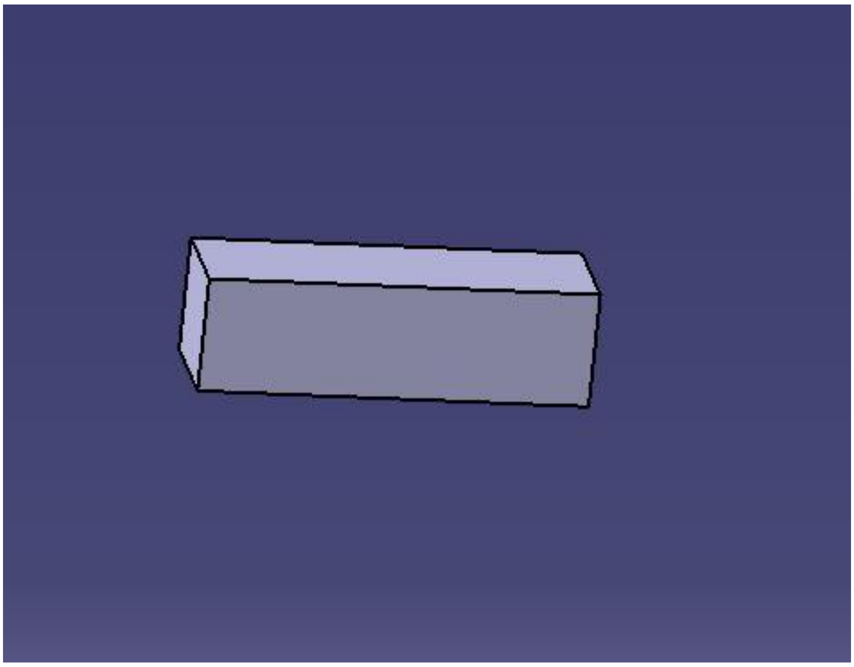




9.7 Appendix G: CAD model OWS Car model A

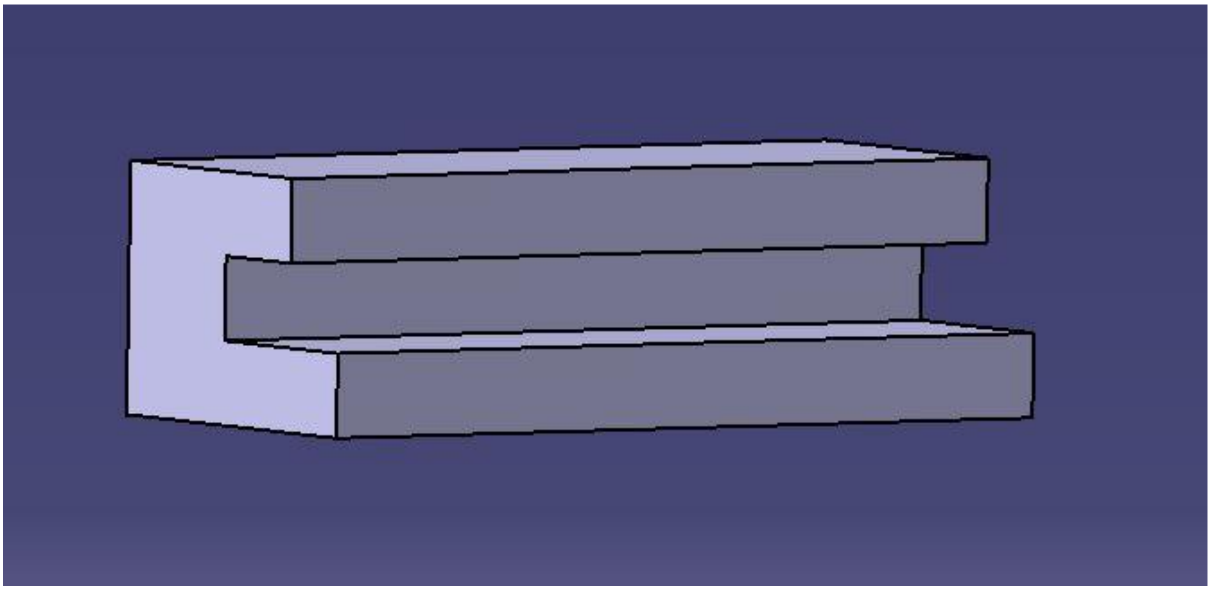
Car model A OWS – Surrounding and reference element

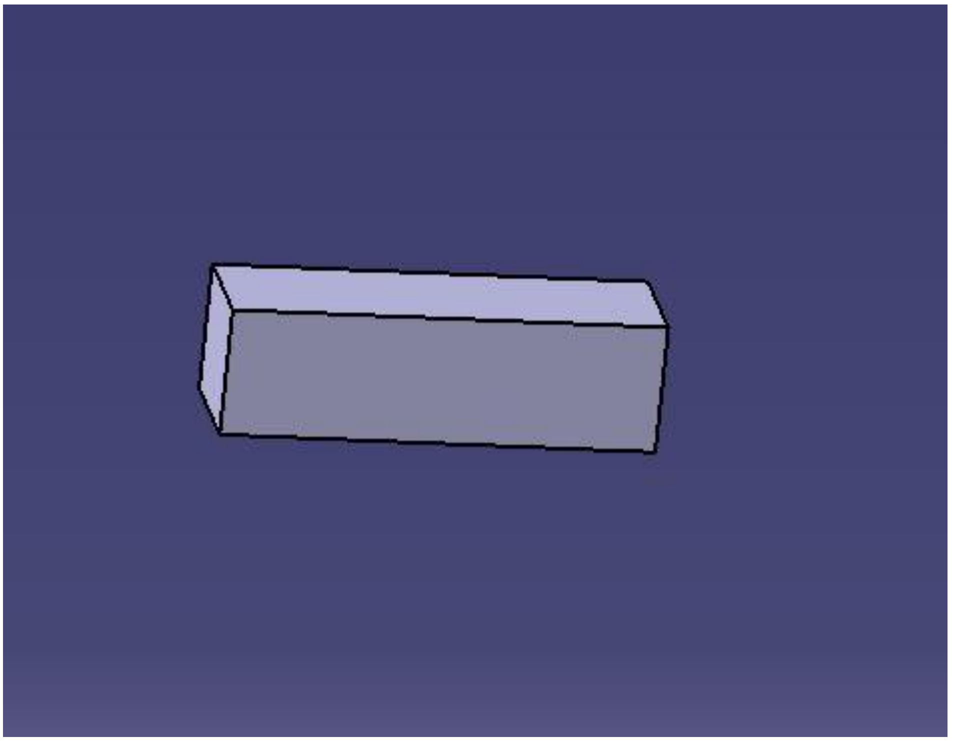




9.8 Appendix H: CAD model OWS Car model B

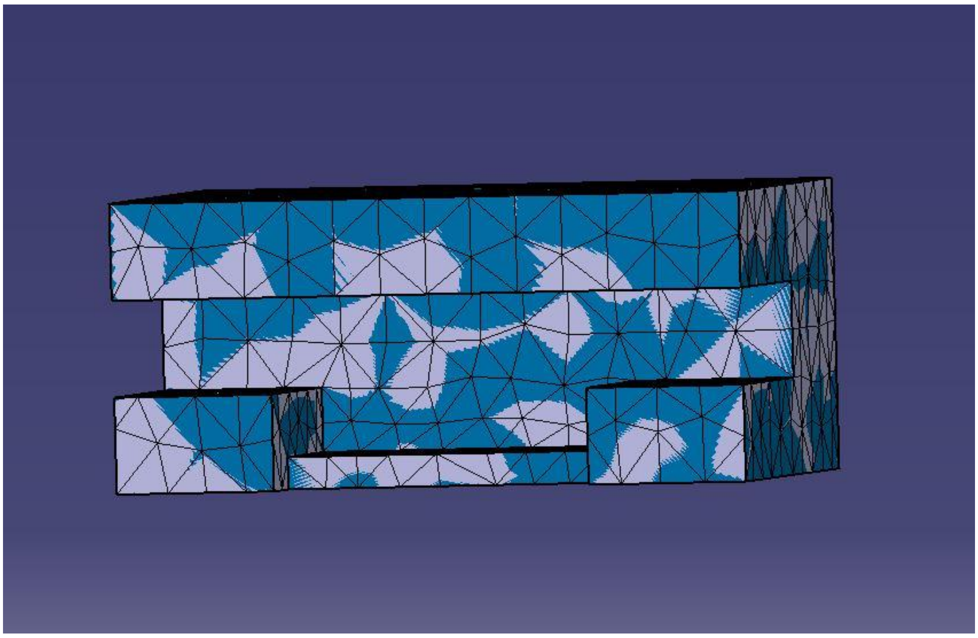
Car model B OWS – Surrounding and reference element.

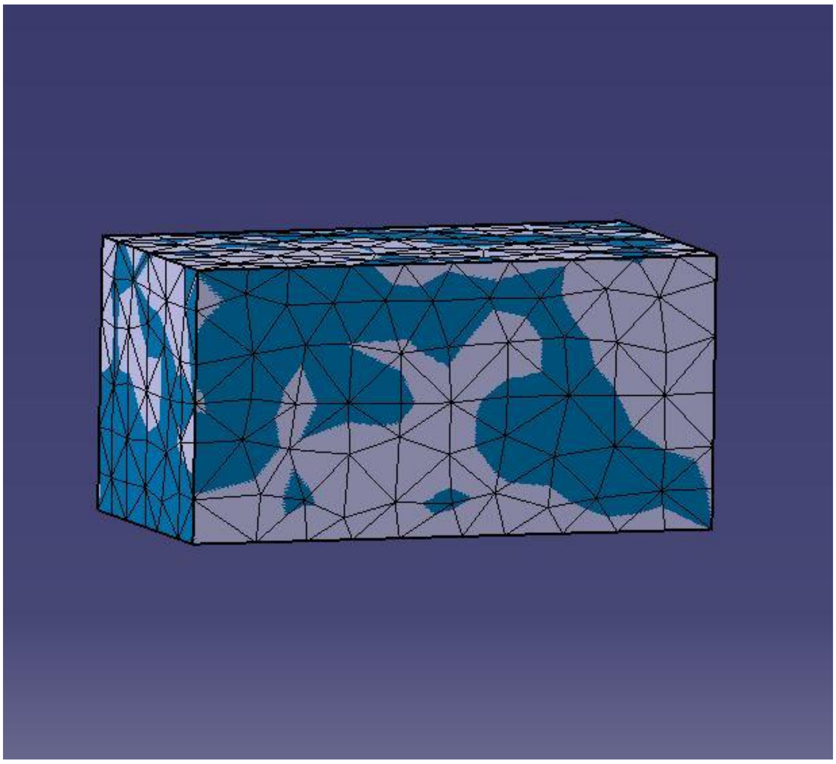




9.7 Appendix I: Mesh GRS Car model A

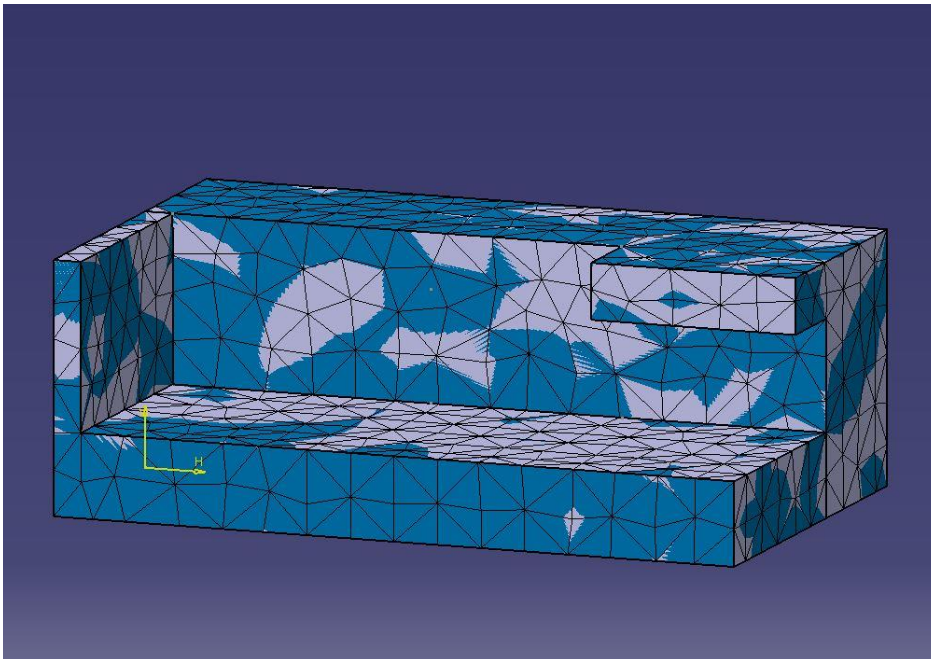
Car model A GRS – Mesh of surrounding and reference element

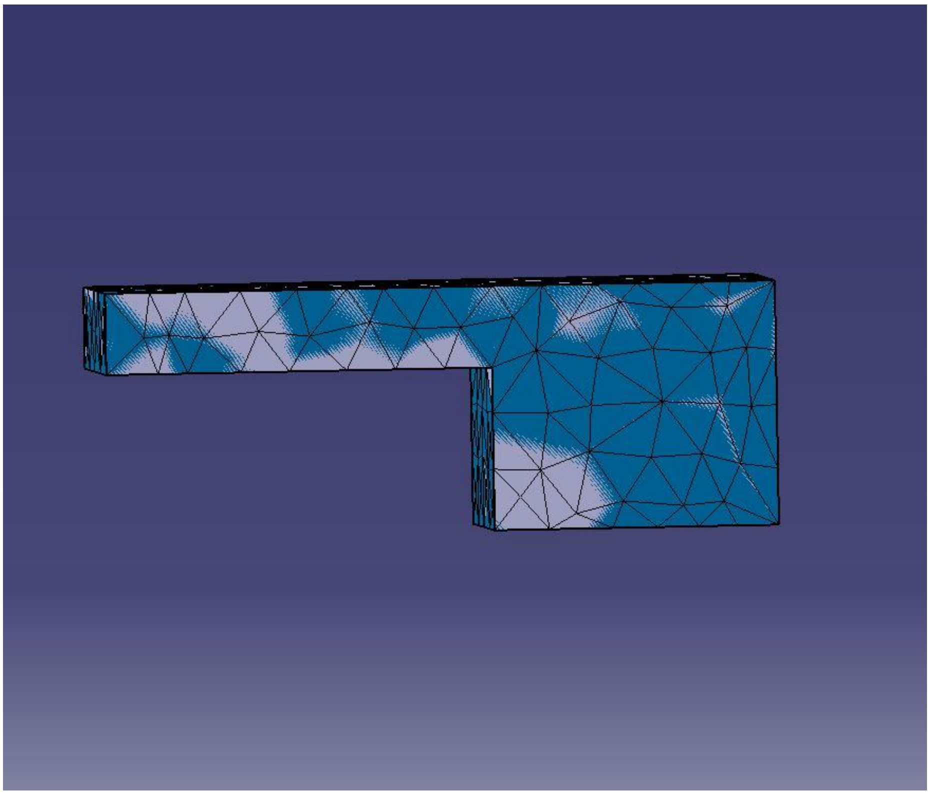




9.8 Appendix J: Mesh OWS Car model A

Car model A OWS – Mesh of surrounding and reference element





9.9 Appendix K: Mesh OWS Car model B

Car model B OWS – Mesh of surrounding and reference element