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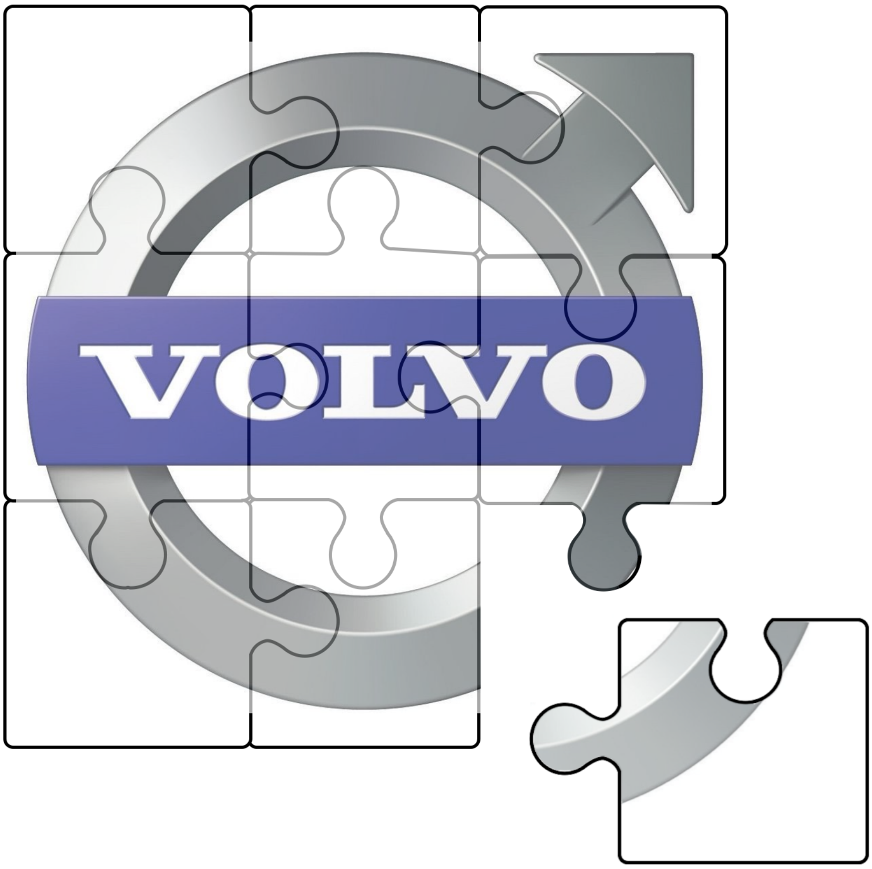

Analysis of Misconstraining during Manual Assembly at Volvo Cars

A Novel Study on the Error Phenomenon and its Contributing Factors Connected to Geometry Assurance

Master’s thesis in Product Development

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021

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Master's Thesis 2021
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Cover:
The title page shows an image depicting a puzzle piece that was developed for the assimilation of the project.

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Abstract

The rising need for increased robustness among products and processes worldwide has made it essential to research areas around geometrical variation and robust design. The presence of humans in the assembly process is inevitable due to the high levels of flexibility they can exhibit. However, the ways humans contribute to geometrical variation in a robust design perspective have not been significantly studied. As an attempt to break this novelty barrier, this thesis focuses on investigating and examining the concept of misconstraining in the context of an error phenomenon at Volvo Car Corporation through a series of case studies, semi-structured interviews, and tests. Following a standard product development process, the main aim of the thesis is to provide proof of concept for misconstraining and develop a framework for analyzing misconstraining from a manual assembly perspective. The test cases present in the thesis have been designed by keeping in mind the parameters involved in the manual assembly process, like assembly sequence and the surrounding conditions. The results have been corroborated by analyzing graphical plots and extensive evaluation of the various case studies.

Ultimately, by utilizing all the information brought to light, the thesis resulted in developing a detailed mapping of the different causes and effects of misconstraining. Furthermore, the tests conducted revealed how the play between the guiding elements leads to geometrical variation in connection to human error contribution and how the change in screw sequence during assembly expedites misconstraining. The thesis concludes with a list of recommendations to tackle misconstraining and the envisioned forms of misconstraining. Also, a solid amount of information vital for future research has been presented with some exciting visualization about the concept moving forward.

Keywords: Geometry assurance, manual assembly, geometrical variation, misconstraining, robustness, assembly sequence, misguiding, system solution, tolerance.

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Last but not least, we would like to thank our friends and family for having supported us in this wonderful journey and for having made our master's here at Chalmers a memorable one.

Erik Arvidsson & Vasanth Kumar,
Gothenburg, Sweden
June 2021

List of Abbreviations

BIW:	Body In White
CAT:	Computer-Aided Tolerancing
CXB:	Basic Assembly Complexity
CXI:	Complexity Index
DOF:	Degree of Freedom
DP:	Design Parameter
FR:	Functional Requirement
GA:	Geometry Assurance
GAE:	Geometry Assurance Engineer
GSU:	Geometri Systemutvecklare
HC:	High Complexity
HRA:	Human Reliability Analysis
MC:	Misconstraining
ME:	Manufacturing Engineering/ Engineer
PII:	Process Inspection Instruction
RCA:	Root Cause Analysis
RDE:	Robust Design Engineering/ Engineer
RD&T:	Robust Design & Tolerancing
RMS:	Root Mean Square
TMU:	Time Measurement Unit
TRL:	Technology Readiness Level
VCC:	Volvo Car Corporation
VGA:	Virtual Geometry Assurance

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1
Introduction

Volvo Car Corporation (VCC) is a global leader in the consumer market and one of the key players in the automotive industry striving towards electric mobility and autonomous driving. To uphold a high level of quality and effectiveness, the demand for accuracy and precision is highly significant. Hence, errors and deviations must be prevented or limited during the early product development phases, mainly to avoid late changes, which might be expensive and time-consuming. This chapter presents the background behind the thesis and the organization where it is studied, the aim, research questions, and delimitations dealt with in the thesis.

1.1 Organizational Background

VCC is a well-known global automotive firm manufacturing cars in the premium segment. Driven by safety technology and innovation, the organization has been a Swedish trademark right from the time the first car rolled off the production line in 1927 (Volvo Cars, n.d.). Under the ownership of Zhejiang Geely Holding of China, VCC has been home to several innovations and improvements with the ultimate goal of making transportation safer and sustainable moving forward. Selling car models in the categories of sedans, versatile estates, and SUVs worldwide, VCC has plants in Sweden, China, Belgium, Malaysia, and the USA. In addition, VCC boasts the pride of having brought to the world the 3-point V-type seat belt, which has saved millions of lives time and time again (Volvo Cars, 2009).

1.2 Project Background

The involvement of humans in the assembly process is inevitable, and humans will always triumph over robots in terms of flexibility in the automotive world. In an article released online, Mercedes-Benz's head of production had expressed a similar notion, "Robots can't deal with the degree of individualisation and the many variants that we have today. We're saving money and safeguarding our future by employing more people." (Gibbs, 2016). Studied in connection to Geometry Assurance (GA), this thesis is a step towards accounting for an error phenomenon termed as misconstraining (MC) in the manual assembly process to develop highly robust cars and have minimal geometrical variation.

This thesis is a part of the research project called AMIGO which aims at performing analysis with manikins for better geometric quality during manual assembly. The

AMIGO project is funded by Vinnova, Sweden. Some previous work has already been done in the AMIGO project on estimating process complexity in the manual assembly process at VCC (Falck, Tarrar, et al., 2017). The drive for this thesis study partly comes from the work of several researchers at the Wingquist Laboratory in Chalmers, who are also involved in the AMIGO project. Some of the prominent areas of research in connection to this topic are geometry assurance in general (Söderberg, Lindkvist, Wärmefjord, & Carlson, 2016), complexity assessment in the manual assembly process (Falck, Örtengren, Rosenqvist, & Söderberg, 2017b), variation simulation (Wärmefjord, Söderberg, & Lindkvist, 2016), geometrical variation management (Schleich et al., 2018) etc. This current step in the AMIGO project aims to analyze MC in the manual assembly process, provide proof of concept, and find ways to account for it early in the product development process.

1.2.1 Sustainability Aspect

The sustainable development goals (SDG), addressed by the United Nations in their drive towards better well-being for both humans and the earth, are relevant for this thesis project in a couple of different aspects. Primarily development goal number nine, focusing on the elements of sustainable industrialization and innovation (United Nations, n.d.) is of high relevance. The AMIGO project, including this thesis, aims to derive more geometrical robust solutions influencing both economic and environmental aspects by reducing material usage (Rosenqvist, Söderberg, & Wärmefjord, 2019), in line with SDG 9.4. In addition, the objective is also to address societal views of employees' working conditions by improving ergonomics which is in line with SDG 9.2, meanwhile, also focus upon how these factors possibly could affect the geometry to improve the robustness of assemblies. The novelty aspect of MC and being a new area of research is in line with goal number 9.5, emphasizing on increase of research and development in the industry (Roser, Richie, & Ortiz-Ospina, 2018).

1.3 Problem Statement and Definition

As a preliminary subjective definition, MC is observed as an error phenomenon caused by inaccuracies in the assembly process or when parts being assembled are out of specification. It is a term studied in connection to GA and is expected to influence the aesthetics and functionality of the component assembled. In most cases, MC is brought to light through geometrical variation in measures such as gap and flush. However, it is essential to understand that the definition of MC is primitive and continuously evolving owing to its novelty.

1.3.1 Aim

It is essential to consider the possibility of MC in the early phases of the product development process like the product design phase to increase robustness, dwindle costs and improve product quality during the assembly process. It is also vital to derive a methodology for preventing or reducing the impact of misconstraining, and this will be one of the sole purposes of this thesis study. The primary goals or aims of this project is as follows:

- Gather information about misconstraining using a variety of data collection techniques.
- Examine and evaluate the impact of misconstraining on geometrical requirements.
- Develop a framework to evaluate the design regarding manual assembly in the early product development phases to reduce the risk of misconstraining.
- Validate the framework or methodology developed.

1.3.2 Research Questions

Preliminary literature review, brainstorming, and discussions within VCC on this novel topic have brought to light the following Research Questions (RQ) to be answered from this master's thesis.

1. What is misconstraining, and what are its prominent causes in the manual assembly process?
2. What are the effects of misconstraining?
3. How does misconstraining influence the geometrical requirements in the product development process moving forward?
4. What methodology/framework can be developed to minimize the risk of misconstraining?

1.3.3 Delimitations

The following delimitations have been taken into consideration for curtailing the scope of this project:

- The study will focus only on the manual assembly activities involved in the assembly line and not on the remaining processes like the automated assembly being carried out in the factory.
- Only misconstraining connected to newly produced Volvo Cars will be studied. This means that long-term consequences, such as water leakage due to dissolved sealing, rust, etc., will not be investigated.
- Parts that are easy to observe during manual assembly will be studied. Manually assembled parts within the cabin, such as the interior, were excluded altogether owing to Covid-19 pandemic restrictions.
- Components subjected to study are assumed to be rigid; non-rigid or compliant behavior will be excluded.

The project presents the need to observe the assembly line up close. However, with the CoVID-19 situation, it has become hard to gain access to the assembly line inside VCC. As a result, the studies and tests were conducted in the measurement room.

1.4 Outline of the Thesis

Exploring the outline, the thesis presents the theoretical framework in Chapter 2 followed by the methodology utilized in Chapter 3. A series of case studies in Chapter 4 and test results in Chapter 5 serve as the base for the discussions presented in Chapter 6. Finally, answering the RQ's in Chapter 7 concludes the thesis.

2

Theoretical Framework

This chapter provides detailed information about the theoretical background and the research connection. This chapter helps grasp the thesis work better and fully understand the studies conducted in the following chapters. The theory presented in this chapter will be further connected to the findings in Chapter 6 to establish the research link altogether. The sections and subsections discussed will also have some interrelationships within themselves. The theory has been studied in connection to this thesis, and its implementation has also been sought after.

2.1 Product Development Process

The product development process described by Ulrich and Eppinger (2012) denotes the significant phases of a project as well as the flow in which the operations are to be carried out, see Figure 2.1. Starting from the primary planning stage, which is defined as phase zero, the product development process steps are executed phase by phase in a sequential manner (Ulrich & Eppinger, 2012). The knowledge acquired on the product development process has been further utilized in this theoretical concept study in Chapter 3 to establish the thesis workflow.

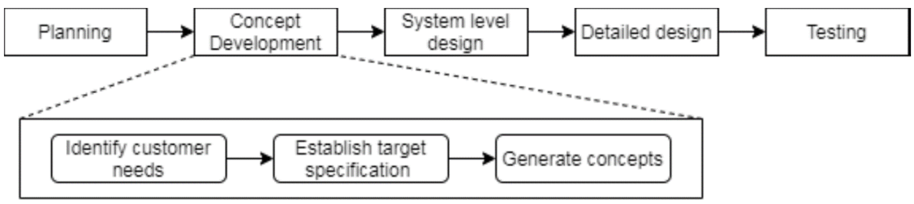

Figure 2.1: Product development process pipeline (Ulrich & Eppinger, 2012).

2.1.1 Concept Novelty and Immaturity

Concept novelty and the corresponding immaturity is reflected in connection to the novel theoretical concept of misconstraining. The evolution of a concept depends on the knowledge available at hand. Usually, the unknowns or uncertainties about a given concept are high during the start of the product development process but gradually reduce with time (Aroonvatanaporn, Hongsongkiat, & Boehm, 2012), as shown in Figure 2.2. This notion, as mentioned in the article, is vital for the assessment of concept maturity. Moreover, as discussed by Mankins (1995), the evolution of a given technology which can also be translated to a concept, involves a lot of development stages. Therefore, a novel concept matures as it moves through these development stages one after the other.

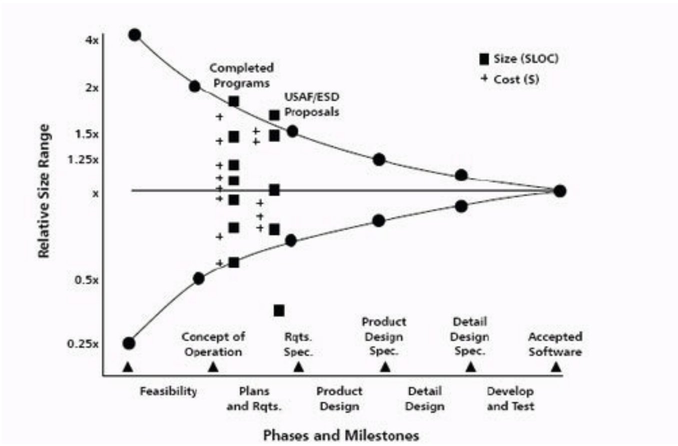

Figure 2.2: The cone of uncertainty (Aroonvatanaporn et al., 2012).

2.2 Geometrical Variation

Observed as a deviation in form and dimension, geometrical variation is vital when it comes to the product development process (Lööf, 2010). Geometrical variation originates from part, and assembly variation and together affects the product (Söderberg, Lindkvist, & Carlson, 2006b). Part variation comes from parts being out of specification due to manufacturing issues; in contrast, assembly variation originates from faulty assembly equipment or variation in how the assembly is carried out (Wärmefjord, Söderberg, Dagman, & Lindkvist, 2020). Also, it is essential to understand that tolerances are allowed limits of variation, whereas any deviation away from the nominal for the part is considered geometrical variation (Schleich & Wartzack, 2017).

2.2.1 Aesthetical Impact of Geometrical Variation

One of the factors that determine the customer's satisfaction while purchasing a car is the aesthetical outlook (Mumcu & Kimzan, 2015). Building a car from scratch involves many sub-assemblies and assemblies at various levels that come together to create one final car in the end. When the base components come together, there exist split-lines that establish the gap in between these components (Wickman & Söderberg, 2010). From a customer's point of view, these split lines will influence the opinion they have regarding the aesthetics of the car and their decision to purchase the vehicle. To ensure a high standard of perceived quality, the measures such as flush, gap, and parallelism are kept within a specific limit and are confirmed by the GA process. In a broader perspective, variation in the manufacturing process as well as robustness concerning design are significant contributors to geometrical variation and indeed influence the perceived quality of the vehicle (Wickman & Söderberg, 2010), as shown in Figure 2.3.

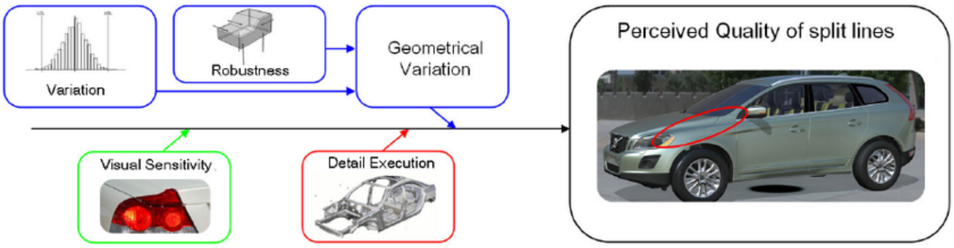

Figure 2.3: Factors contributing to perceived quality of split-lines (Wickman & Söderberg, 2010).

2.3 Geometry Assurance

Geometry Assurance (GA) has evolved over the years and now finds itself a core part of the automotive industry. During the early years, people used their intuition and experience when it came to robustness and GA since they had no digital tools to assist them. But now, with the advent of many sophisticated software tools like RD&T (RD&T Technology, 2021), GA has become an essential part of the product development process (Söderberg et al., 2016). GA includes different activities to decrease the effect of geometrical variation. The tasks can be conducted in all stages of the product realization loop, influencing the quality of products by optimizing the geometrical variation in the various phases of the product life-cycle (Söderberg et al., 2016), illustrated in Figure 2.4.

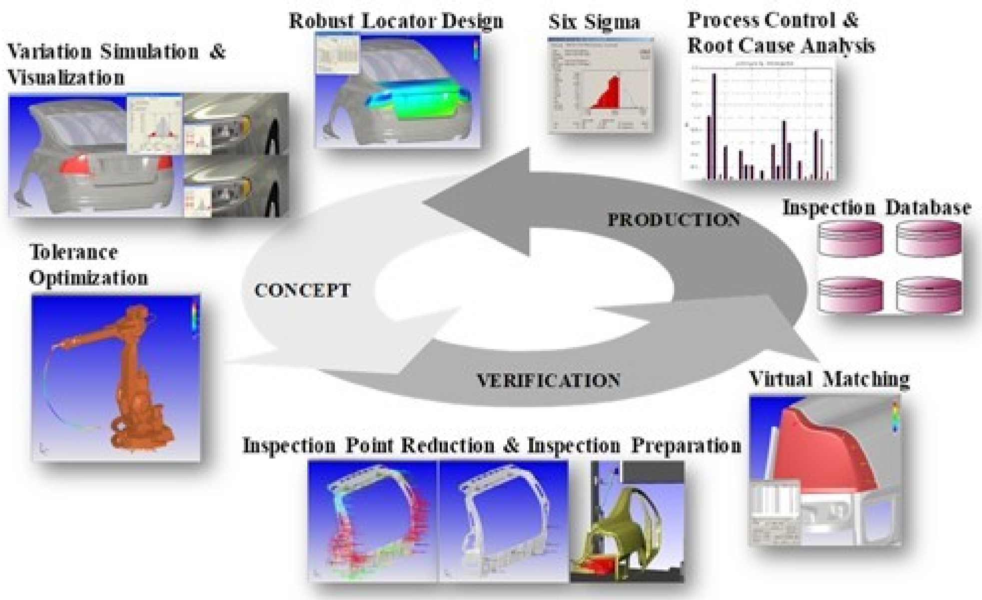

Figure 2.4: Geometry assurance activities (Schleich et al., 2018).

The concept phase aims to optimize the concepts and achieve a robust design based on available data. The verification phase is dedicated to testing and physically verifying the product and the production system. Finally, in the production phase, improvements to the production process are set, and the focus lies within data collection, discovering errors, and improving the production (Söderberg et al., 2016). Hence, GA and geometrical variation affect many of the organization's different actors, from design to manufacturing, assembly, etc. (Schleich et al., 2018).

2.3.1 Geometry Assurance Simulations

Some of the methodology utilized in the GA-software RD&T is based upon Suh's independence axiom (Söderberg & Lindkvist, 1999). The theory about axiomatic design was first published in 1978 and has since influenced engineering design theories and making the design more scientific rather than an art form (Farid & Suh, 2016). The independence axiom is the first of two axioms presented by Suh with the goal of *"Maintain the independence of functional requirements (FRs)"* (Farid & Suh, 2016). Implementation of the axiom and its theory in a geometry perspective grants designers to improve the design by assessing the geometrical sensitivity of assemblies, determine the origins of source variation, and connect them to the overall robustness (Söderberg & Lindkvist, 1999). The axiomatic design connects the relation between the functional requirement (FR) and design parameter (DP) through the design equation, see Equation (2.1). By studying the design matrix (B), design analyses can be performed per the independence axiom (Farid & Suh, 2016).

$$\Delta \boldsymbol{FR} = [B]\Delta \boldsymbol{DP} \tag{2.1}$$

Dependencies between the FR_i and DP_j are determined if the design matrix $B(i,j)$ yields nonzero elements (Farid & Suh, 2016). Following Suh's 1st axiom, a good design is uncoupled, meaning that every output is defined by one single input, resulting in a diagonal design matrix (Söderberg & Lindkvist, 1999), see Equation (2.2). Moving on, $B(i,j)$ is now to be seen as the partial derivative $\partial FR_i/\partial DP_j$.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} B_{11} & 0 & 0 \\ 0 & B_{22} & 0 \\ 0 & 0 & B_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \tag{2.2}$$

Furthermore, a design could still be deemed acceptable to the independence axiom if the design matrix is or can be transformed into a lower triangular one, resulting in a design that is called decoupled (Farid & Suh, 2016; Söderberg & Lindkvist, 1999), see Equation (2.3).

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} B_{11} & 0 & 0 \\ B_{21} & B_{22} & 0 \\ B_{31} & B_{32} & B_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \tag{2.3}$$

From an assembly point of view, the uncoupled and decoupled design can be exemplified with parallel and serial assembly solutions, respectively. Figure 2.5 illustrates the two different types. The matrix elements highlight the geometrical dependencies between DP, in this example illustrated with the location scheme, denoted as P-frame, and the FR now exemplified as the position (Söderberg, Lindkvist, & Carlson, 2006a).

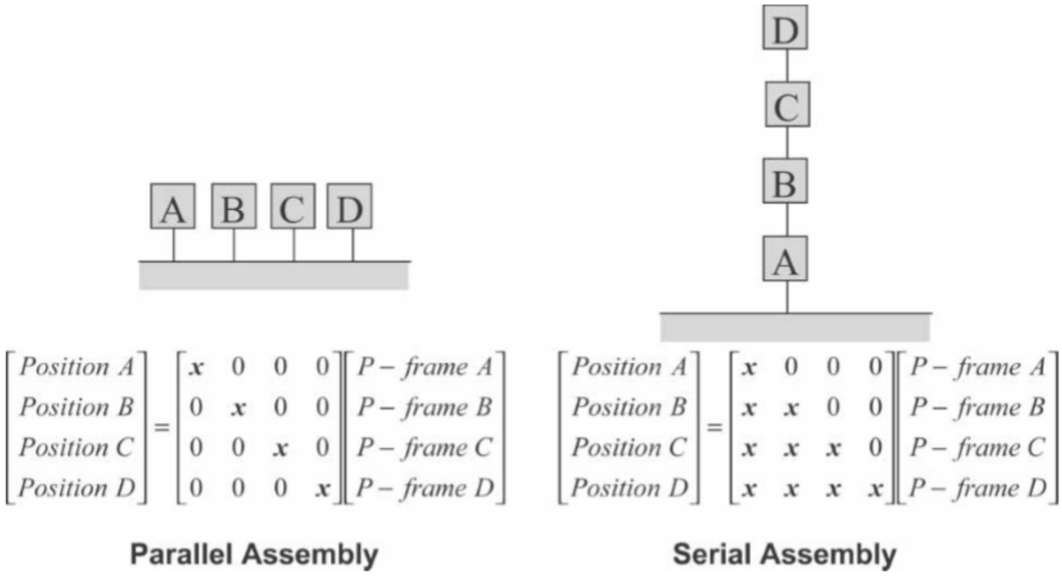

Figure 2.5: Parallel and serial assembly (Söderberg, Lindkvist, & Carlson, 2006a).

Although, perfect systems, as described earlier, are in many instances hard to achieve, especially with complex assemblies in mind, resulting in a matrix with dependencies not equal to the two previous cases (Söderberg & Lindkvist, 1999). This is referred to as a coupled design and is something one should strive to avoid due to the difficulties of tuning and controlling these designs. Therefore, minimizing the coupling between DP:s and FR:s is most often an effective way to enhance the robustness (Söderberg et al., 2016). Additionally, products are, in most cases, a mixture of the two assemblies types (Söderberg, Lindkvist, & Carlson, 2006a).

2.3.2 Location Schemes

A location scheme makes it possible to lock the six degrees of freedom (DOF) that individual parts and sub-assemblies possess in 3D space. There are different methods in achieving this, expressed by Söderberg, Lindkvist, and Carlson (2006a). Nevertheless, the 3-2-1 location scheme is one of the most utilized and also the least coupled (Söderberg, Lindkvist, & Carlson, 2006a). Figure 2.6 is showcasing an orthogonal 3-2-1 location scheme and indicates the part location points. Firstly, the three initial points, often indicated with A1-A3, lock one translation and two rotations, namely translation in Z (TZ), rotation around X (RX), and rotation around Y (RY). Secondly, the two points B1 and B2 lock one translation in X (TX) and the remaining rotation around Z (RZ). Lastly, point C1 finally completes locking by obstructing the last translation in Y (TY) (Söderberg, Lindkvist, & Carlson, 2006b).

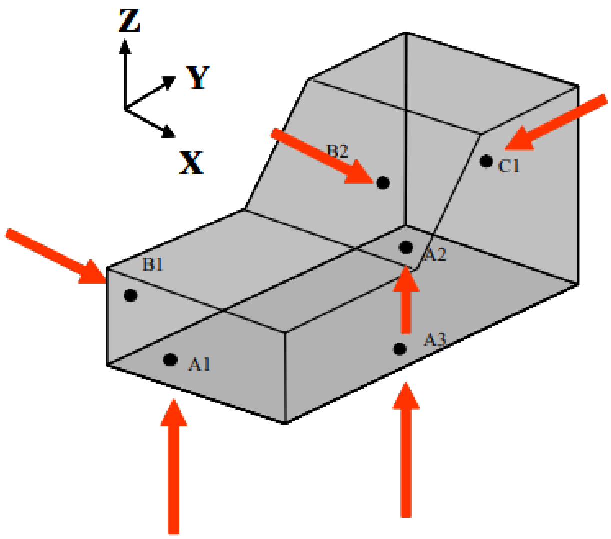

Figure 2.6: Orthogonal 3-2-1 location scheme (Söderberg, Lindkvist, & Carlson, 2006b).

The aim is to select location points as far from each other as possible, within the available space, to optimize the points and maximize robustness. However, this hypothetical optimum of having orthogonal locating points could be hard to achieve due to insufficient design freedom caused by adjacent components and systems. Also, location schemes such as the 3- or 6-directions could become more proficient at accounting for non-orthogonality but in reality these schemes make the system more coupled. Furthermore, most location schemes are coupled by default, meaning that each point controls more than one DOF (Söderberg, Lindkvist, & Carlson, 2006a), contradicting the independence axiom.

2.3.3 Tolerances Allocation

The manufacturing and assembly processes affect and increase the geometrical variation, thus, influencing functional, aesthetical, and assembly demands (Söderberg et al., 2016). Though the manufacturing accuracy has grown over the years, geometrical variations are still recognized in many produced products (Schleich et al., 2018). To enhance the quality and performance, meanwhile decreasing cost, defining part tolerances needs to be considered. However, defining a small tolerance range might increase quality, but it may also increase the cost. Hence, the circumstance and the parts present need to be addressed when allocating the tolerance. Typically, the tolerance allocation is performed relatively late in the product design process. Nevertheless, it has been described that 60% of changes made in the late development of a novel product can be related to tolerances, vague or sensitive concepts. Defining a robust concept early on can therefore decrease the cost associated with the late changes (Söderberg et al., 2016).

2.3.4 Rigid and Non-Rigid Variation Simulation

The variation analysis simulation can be utilized early in the PD process to assess geometrical outcome and the influence variation has on assembled products and sub-assemblies (Wärmefjord, 2011). From the GA point of view, the variation simulation is a method to assess how set tolerances will influence the location schemes, i.e., anticipated variation of produced parts (Wärmefjord, 2011). This is done by applying the statistical model known as Monte Carlo to produce random samples and thereby generating the variation (Rosenqvist, Falck, Lindkvist, & Söderberg, 2016). The constructed variation is often used as a basis for predicting the critical dimensions, such as gap, flush, and parallelism measures, using entities like capability, distribution, mean value, and variation (Wärmefjord, 2011). GA software and their practical implementation of computer-aided tolerance (CAT) tools in the industry is often done with the help of rigid simulations. This technique enables the geometry assurance engineer (GAE) to compute how the variation of parts influences the overall robustness of designs and assemblies. These simulations are commonly conducted by studying the variation of the positioning system (Söderberg, Lindkvist, & Carlson, 2006a). Choosing the correct locators and the positioning system has become increasingly important with today's complex products to withstand geometrical variation and create a robust design (Söderberg, Lindkvist, & Carlson, 2006a).

The CAT-software RD&T allows taking non-rigid behavior into account while assessing the robustness (Söderberg, Lindqvist, & Dahlström, 2006). These simulations demand a finite element mesh along with the corresponding stiffness matrices (Söderberg, Lindqvist, & Dahlström, 2006). After being imported into the CAT software, behavior like contact modeling (Lindau, Lorin, Lindqvist, & Söderberg, 2016), fixture variation (Wärmefjord, Carlson, & Söderberg, 2016), joining processes (Wärmefjord, Söderberg, Lindau, Lindqvist, & Lorin, 2016), and different materials and their properties can be taken into consideration (Wärmefjord, Söderberg, & Lindkvist, 2016). One methodology for assessing a non-rigid behavior is extending the positioning system to take the compliant behavior into account. Hence, the N-2-1 location scheme could be utilized, where N is substituted for the desired number of constraints (Söderberg, Lindqvist, & Dahlström, 2006). Furthermore, it is also possible to view more than one direction as non-rigid; in such case, the N-O-P location scheme could be employed (Söderberg, Lindqvist, & Dahlström, 2006). Utilizing non-rigid variation simulations increases the accuracy of simulations made on compliant parts. Though, it adds complexity and increases the computational time required (Wärmefjord, Söderberg, Lindau, et al., 2016).

2.4 Manual Assembly

The influence brought about by human beings in the assembly process has been a topic of study for quite some time. Even though it is possible to automate a large percentage of the production process, most of the final assembly steps in the automotive industry are performed manually by humans (Gibbs, 2016). This section will briefly introduce the theory behind the various manual assembly elements connected to this thesis.

2.4.1 Assembly Complexity

Assembly complexity can be perceived as the difficulty of performing a given task correctly as per the intended system solution. It is a wide-open area of study that involves many factors to be taken into consideration. As presented by Falck, Örtengren, et al. (2017b), ergonomics and cognitive requirement for performing the tasks involved in the manual assembly process are primary contributors to assembly complexity, and there is a growing need to attend to these factors on a detailed level. However, sometimes it is also the performance requirement or tight tolerance requirements that magnify the assembly complexity, and this indirectly would cause quality errors and increased pressure on the workers involved (Falck, Örtengren, et al., 2017b).

Assembly Complexity and Assessment

Assembly complexity comes into a more significant effect mainly in the manual assembly process and can potentially lead to poor quality and errors in the end product (Falck, Örtengren, et al., 2017a). It is possible to measure assembly complexity as a phenomenon since it has many quantifiable factors attached to it. Developed with the overall goal of increasing assembling quality and efficiency by reducing assembly errors, both Basic Assembly Complexity (CXB) and Complexity Index (CXI) are effective methods of assessing assembly complexity (Falck, Tarrar, et al., 2017). However, as presented by the authors in the same article, the CXB method is best suited for evaluating installation conditions, whereas the CXI method is ideal for examining existing assembly conditions in the manufacturing process.

Other attempts at measurement of assembly complexity and how it would affect the robustness of the design are presented by Rosenqvist, Falck, and Söderberg (2015). In the article, the authors have proposed a framework consisting of 16 High Complexity (HC) criteria to help evaluate the impact that manual assembly complexity would have on the geometrical stability of the design. The 16 HC criteria have been developed as part of the interface in the RD&T software, where values for robustness-related factors like stability and complexity are arrived at based on the yes or no answers provided to the criteria points. The result obtained is a calculated Root Mean Square (RMS) value. In RD&T, general location scheme sensitivity, or the part positioning goodness, is determined as the RMS value of the influence that the location scheme has on the geometry (Söderberg & Lindkvist, 1999). It is always preferred to have a lower normalized RMS value at the end since a smaller value implies a more robust system (Rosenqvist et al., 2015).

The 16 HC Criteria

This section of the report will briefly mention the theory behind the arrival of the 16 HC criteria and explain how these criteria must be assessed. Necessary interpretations for all the criteria points have been provided in Appendix A. The following HC criteria were influential in framing the entire project scope and framework. The following criteria points have been tested and analyzed in several industries like NEVS, Scania, VCC, etc., on different parts over the years (Falck, Örtengren, Rosenqvist, & Söderberg, 2016; Rosenqvist et al., 2015), see Table 2.1.

Table 2.1: 16 HC criteria for the assessment of complexity in assembly tasks (Falck, Örtengren, et al., 2017a)

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 ergonomics conditions implying risk of harmful impact on operators
8	Operator dependent operations requiring skilled operators to be properly done
9	Operations must be done in a certain order
10	Visual inspection of fitting and tolerances, i.e. subjective assessment of the quality results is required
11	Accuracy/precision demanding tasks
12	Need of adjustment
13	The geometric environment has great variety (tolerances), i.e. the level of fitting and adjustment varies between the products
14	Need of clear work instructions
15	Soft and flexible material (that is not form-resistant)
16	Lack of (immediate) feedback of properly done work by e.g. a clear click sound and/or compliance with reference points

2.4.2 Assembly Sequence

Assembly sequence in the manual assembly process plays an important role and is a substantial contributing factor to deviations or errors in general (Rosenqvist, Falck, Söderberg, & Wärmefjord, 2013). There is a considerable probability for deviations to occur in the manual assembly process, and it has been observed that the actual error at the end of the process is relatively higher than the predicted error, and a prime reason for it has been assembly sequence (Rosenqvist et al., 2013). The assembly sequence is also directly connected to assembly complexity, and together with assembly ergonomics, it becomes a prime factor for determining the complexity of the manual assembly process (Zaeh, Wiesbeck, Stork, & Schubö, 2009).

As mentioned by Zaeh et al. (2009), it is imperative to establish the assembly sequence by taking into consideration the physical and mental health of the operators involved and also the current state of the equipment available for the processes to be carried out. The assembly sequence, if not followed, has proven to bring about a deviation in the assembly process and, as a result, a significant gap between the CAT simulations and the actual output measurements (Rosenqvist et al., 2013).

Assembly Sequence Establishment in Volvo Car Corporation

At VCC, the assembly sequence is a part of the assembly instruction presented as a Process Inspection Instruction (PII) and is preset for a given production model as shown in Figure 2.7. The critical element in the PII is the operation description, where importance must be given to information clarity and the sequence in which the operations are prescribed. This is the sequence in which the assembly operations are carried out, and each of these operations also has a specific Time Measurement Unit (TMU) assigned for their completion. Due to confidentiality, the actual TMU has been masked in Figure 2.7. The notations 'No' and 'Ref' are utilized to identify the operations in the visual variant of the assembly instruction document.

MANUFACTURING ENGINEERING PROCESS-/INSPECTION INSTRUCTION [redacted]

OPERATION

Type	EL	No	Ref	CC	Operation Description	ESDS	Stn No	Variant	TMU	Intro Week
M		08	A		Add one (1) washer to LH side cap screw.				[redacted]	
S		10	B	-	Assemble one (1) cap screw to BIW					
M		20	C		Assemble fixation frame to BIW					
T		30			Check if the gasket on the lamp is in correct position (in order to prevent waterleakage)					
M		40	D		Assemble rear lamp to BIW. Steer in the upper guiding pin , and steer in the lamp against the cap screw. Push the lamp forwards to correct position so the third hand clips grips					
M		60	E	-	Assemble the spring screw through the lower hole in fram and pree enter it 3 turns					
S		70		-	Tighten one (1) spring screw according to specification					
S		80	F	-	Tighten one (1) upper screw to specification.					
M		508	G		Add one (1) washer to RH side cap screw.					
S		510	H	-	Assemble one (1) cap screw to BIW					
M		520	I		Assemble fixation frame to BIW					
T		530			Check if the gasket on the lamp is in correct position (in order to prevent waterleakage)					
M		540	J		Assemble rear lamp to BIW. Steer in the upper guiding pin , and steer in the lamp against the cap screw. Push the lamp forwards to correct position so the third hand clips grips					
M		560	K	-	Assemble the spring screw through the lower hole in fram and pree enter it 3 turns					
S		570		-	Tighten one (1) spring screw according to specification					
S		580	L	-	Tighten one (1) upper screw to specification					

STRUCTURE

Ref	QTY	Part No	Part Name	Traceability	Variant	CO No	CO Iss	Intro Week
A	1	00986516	WASHER 6,7*14*1		[redacted]			
B	1	31656618	CAP SCREW M6X24,7					

[redacted]

Printing date 24/02/2021

Figure 2.7: Process Inspection Instruction sheet. (Certain sections have been masked as per company guidelines).

2.4.3 Assembly Ergonomics

Ergonomics involves the notion about what posture a human assumes while performing an activity. Since the manual assembly process involves people all along, ergonomics is seen to affect the assembly complexity in a big way (Rosenqvist, Falck, & Söderberg, 2012). Nowadays, it is possible to simulate the postures that the worker would assume when performing the actual assembly using digital tools.

Moreover, these tools elucidate the importance of certain assembly factors such as assembly ergonomics that need to be incorporated when considering the locating scheme and geometrical stability calculations in the robust design process (Rosenqvist et al., 2012). Furthermore, professional tools like the IPS path planner can help visualize the ergonomic way to carry out assembly operations with the help of a mannequin (Hanson, Högberg, & Söderholm, 2012).

2.4.4 Human Error

Human error is an inevitable part of the manual assembly process. Cognitive functions are put to the test during the assembly process, and it is not easy to model human behavior based on the component being assembled (Brolin, Thorvald, & Case, 2017). Assembly performance is known to drop if the workload is lesser than the usual standard or if it increases by several folds (Saptari, Leau, NG, & Mohamad, 2014). The same article suggests that the correlation between humans committing errors or poor performance and workload follows an inverted U type relationship in general, as shown in Figure 2.8. Human errors can be caused due to a multitude of factors like time pressure, ergonomics, and tool placement (Saptari et al., 2015). It was proven in this article through case studies that time pressure and ergonomics were prime contributors to the occurrence of human errors, just as Lin, Drury, and Kim (2001) expresses the relationship between assembly ergonomics and quality errors in the manual assembly process.

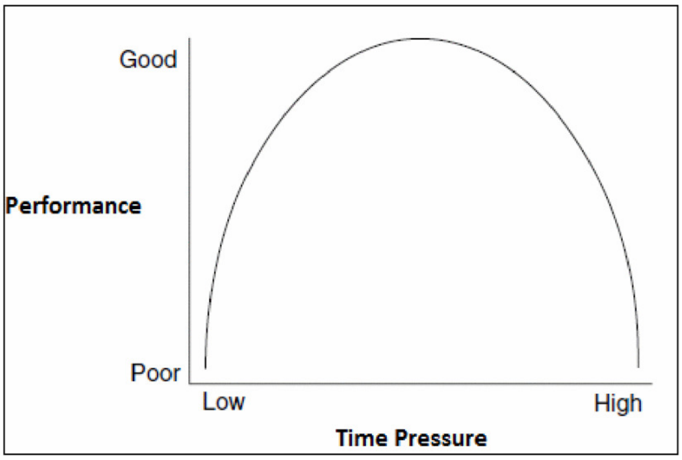

Figure 2.8: The inverted U type relationship between workload and performance (Saptari et al., 2015).

With the study about the occurrence of human errors comes the need to look into how reliable humans are in terms of performing an excellent job with the manual assembly tasks (Pasquale, Miranda, Neumann, & Setayesh, 2018). As presented in the article, the Human Reliability Analysis (HRA) framework helps predict the probability of human error and its contributing factors. Furthermore, case studies in the article utilizing the HRA framework indicate human errors as causes for quality defects and a drop in productivity.

2.5 Misconstraining

The term misconstraining originates from a word used in the industry, known in Swedish as Tjuvstyrning. Tjuvstyrning was introduced to this thesis through discussions, interviews, and visiting the assembly plant and has been described as; when components unintentionally guide other components. These situations could be easy to find while inspecting the virtual representation of the component by looking for collisions. However, assessing the same issue during running production is challenging due to the multitude of possible causes, hence, the importance of this thesis project. Prior to the AMIGO project, research has been made into the field of assembly complexity, framing it into 16 HC criteria (Falck, Örtengren, et al., 2017b), as described in Section 2.4.1.

3
Methodology

This chapter of the report elucidates the operational workflow utilized in the thesis and the methodology behind the steps involved. Starting from the inspiration behind the visualization of the problem right until the test methodology employed, the chapter gives the collective thought process of the approach taken. In addition, it provides information on the framework used for data collection. Certain subsections presented here are based on intuition, while the rest are based on product development practices and principles. The methods mentioned in this chapter were utilized to arrive at results in Chapter 5 that ultimately helped answer the RQ's in Chapter 7.

3.1 Novel Concept Development

This thesis, with the aim of studying a novel theoretical concept, draws much of its methodology in close connection to the product development process cycle described by Ulrich and Eppinger (2012). This is an established method and provides a holistic approach exhibiting the various steps involved in the product development process. The thesis's operational workflow mainly comprised the planning, data collection, and concept development phases, with utmost importance given towards accumulating as much information as possible concerning MC. With the aims of the thesis kept in mind, the following workflow was established as shown in Figure 3.1. The relevant subsections are mentioned in the individual boxes on the figure and have been elucidated further in this chapter.

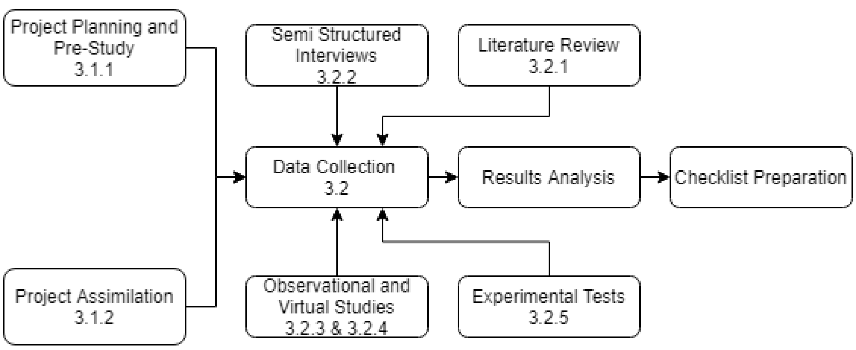

Figure 3.1: Established thesis workflow.

It is essential to understand that the process followed here is not the ideal product development process comprising all the standard steps. However, to suit the nature of the topic being dealt with, the steps utilized are a modified version of the actual product development process and are scientifically valid.

3.1.1 Project Planning and Pre Study

Starting with pre-study on MC, a virtual mind-map was developed through brainstorming. Being a novel concept, there was not much relevant material readily available to begin with initially. Hence the pre-study stage involved concept understanding by exploring all the available perspectives connected to MC without filtering out any available content. The project planning stage plays a vital role in any project as it establishes the workflow and helps keep track of the milestones and checkpoints to be covered over time (Ulrich & Eppinger, 2012). The thesis's primary stages and the various steps involved were planned and drafted using a Gantt chart as shown in Appendix B. The Gantt chart was regularly revised at the start of every week, and the revision was primarily done by reflecting on the previous week's progress and brainstorming on the future work to be done. The Gantt chart presented the way forward in many stages of the thesis and served as an essential planning tool throughout.

3.1.2 Project Assimilation

The assimilation of the concept of MC was done using visualization techniques. The visualization concerning MC was driven by literature, brainstorming, and the use of puzzle pieces. The idea of visualizing MC through the concept of puzzle pieces helped achieve a better understanding of the concept and, at the same time, made it easy to explain the topic in brief to others while collecting information. The following three sources triggered the thought process about MC.

Source 1
Parts being out of specification was envisioned as one of the primary causes of MC. An incorrect mounting or a dimensionally incorrect component will disrupt the assembly in a given region. For example, as shown in Figure 3.2, the lower right puzzle piece has an excess stem on the left side which means it will be impossible for it to be assembled with the rest of the pieces as required. Hence, the puzzle will remain incomplete overall due to this single piece being out of specification. This is one of the sources that inspired the thought about MC and its causes.

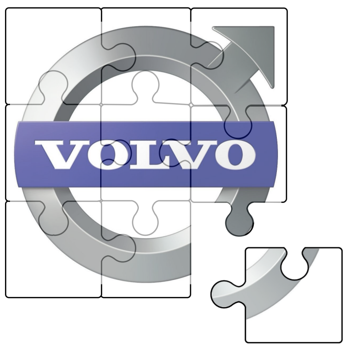

Figure 3.2: Puzzle pieces being out of specification.

Source 2
On a completely different thought, if the puzzle piece had been larger, it would have collided with the surrounding pieces and caused deformation when forced into place, which was hypothesized to be a form of MC. A similar case is also the possibility that when the pieces are slightly smaller in size, they lead to misguiding. Figure 3.3 explains this thought process with the same example of puzzle pieces. The oversized and undersized pieces have been presented on the right and left sides of the main piece.

Figure 3.3: Issues with the size of puzzle pieces.

Source 3
Another thought that followed about MC was that there might be inaccuracies during the assembly of the puzzle pieces. In this situation, the wrong piece with the exact leg placements gets fixed onto a specific position. In this case, even though the puzzle is fully complete, the overall picture would not match the required solution. This is the case where the inaccuracies in assembly lead to a situation where the intended system solution is not satisfied, and the result has been altered even though the parts are all assembled as shown in Figure 3.4.

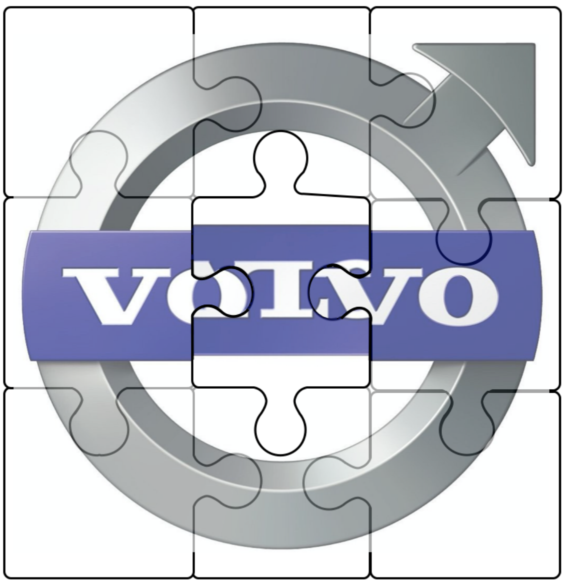

Figure 3.4: Incorrect piece assembled in the middle. Notice that the L is upside down.

3.2 Data Collection

Data collection is an integral part of the product development process pipeline since it predominantly drives the further stages of development (Ulrich & Eppinger, 2012). Data collection can be done in various ways, and it was necessary to discover the right set of tools that would suit the specific nature of this thesis. Looking back at the different methodologies available for data collection as mentioned by Malhotra, Nunan, and Birks (2017), only the primary data collection approach suited the nature of this thesis since the task at hand was to study a novel theoretical concept without much data readily available. As described by the authors in the article, primary data refers to data that is unearthed by the researching group precisely connected to the problem being dealt with.

As expressed by Ulrich and Eppinger (2012), surveys, interviews, tests, analysis of previous research, and focus group discussions are the most widely used tools for data collection. It was discovered that the approach of surveys and focus groups would not be suitable for the nature of this thesis. This was because the thesis aims to study a novel concept with no direct research conducted before this thesis. Also, collecting large data sets through surveys would be ineffective since the phenomenon is relatively unknown and studied explicitly from a GA perspective. The categorization, segregation, and evaluation of survey results would ultimately become time-consuming and might not produce high-yielding results or conclusions.

3.2.1 Literature Review

Owing to the novelty of the concept, as discussed before, the literature available for assessment was at a higher level. Since the articles were on topics connected to MC and not directly on the topic, the literature review process was challenging. It presented its own set of difficulties, but a holistic approach towards the concept helped obtain a rich source of literature. A data extraction spreadsheet was used to aid the collection and knowledge management. The spreadsheet was filled with information such as author(s), source, and a summary of the researched literature. Apart from stating the importance and relevance, this document helped minimize knowledge waste and the risk of searching for the same material twice. This literature study aimed to derive a definition of the topic and what should be included in it as well as assist in mapping defects or miss-constraint errors within the industry to their causes and sub-causes.

3.2.2 Interview Methodology

To elicit information and gather knowledge about MC and other relevant topics, interviews with people from academia and VCC employees were conducted, see Appendix C. Interviews as a data collection method are excellent when exploring complex and subtle phenomena that rely on experts and their knowledge acquired during their careers to interpret and understand phenomena (Denscombe, 2014). This type of knowledge is often referred to as tacit. According to Garcia and Sosa-Fey (2020), tacit knowledge exists in the minds of the persons and is gained through experience and managed by sharing it between individuals. Since the research regarding MC is at its nascent stage and text written regarding the topic is limited, interviews were deemed as the best approach to collect information. These interviews were following a predetermined semi-structured interview style. This allowed for the questions to be developed as the project progressed, meaning that the questions can be changed depending on the answers from previous ones (Denscombe, 2014). A semi-structured interview also permits flexibility in terms of the order in which questions are being put forward, giving the interviewee more freedom to elaborate on certain topics (Denscombe, 2014). Table 3.1 poses as an example of questions asked during the interviews, see Appendix D and E for a complete representation of the initial interview guides.

Table 3.1: Example of posed questions during interviews.

Type	Questions
Open-ended	What is your perception about misconstraining?
	When do you think misconstraining becomes a problem?
Probes	Could you explain further?
	Is it possible to give an example?
Follow-up	If interpreted you correctly...
	To summarize what has been said...

Furthermore, the semi-structured interview allowed probing to get elaborated answers and allowed for follow-up questions to sort out potential misinterpretation and check whether the answers were correctly understood. With the approval from the interviewee, all interviews were recorded. Field notes were taken in the case of not getting the authorization, or the location prevented recording. These notes were immediately afterward turned into a text summarizing the critical findings.

Initial interviews

The primary purpose of the initial interviews was to gather knowledge and perceptions on MC but also to find out whether the interviewee would be suited for further questioning in an in-depth interview. The initial interviews were conducted in English with both the thesis students participating, whereas one was acting as the interviewer while the other noted down essential keynotes. These interviews were held both online using Teams and face to face whenever possible. Eight different interviewees' were questioned, some on multiple occasions, making for ten interviews in total.

Industrial case interviews

To collect information on actual case examples that have occurred within VCC, interviews within the Robust Design Engineering (RDE) team were performed. This information could later be used to ease the explanation of the phenomenon in addition to helping to sort out potential causes of the problem. The case interviews were held one to one in Swedish to ease the interviewees' explanation of the issue and not disregard anything important. The recording was later transcribed for the same reason and later summarized in an English version. The interviews were conducted online through Microsoft Teams, and Teamcenter Visualization Mockup (Siemens, 2021) was used as a mediating tool to increase the understanding further and to explain crucial elements and what went wrong. Three industrial case studies were conducted with VCC employees based on their knowledge and experience working with the specific components.

3.2.3 Observational Research Methodology

Observational research is mainly performed because a visual picture of how something is done is far more beneficial than just interviewing about how it is done from the operator. To say is not to do, and this is indeed the drive behind the observational studies conducted in this thesis. The technique of observational research used in this case is called participant observation which is used primarily to understand the nature of the processes and the work patterns without informing the operators what is being studied (Denscombe, 2014).

3.2.4 Virtual Study Methodology

Different software tools within VCC have been utilized during the project to evaluate potential parts to study concerning MC and geometrical variation. Team Center Visual Mockup has been the main contributor to getting a better picture of parts, locating systems, fasteners, etc. To gain access to the Teamcenter software tool at VCC, a one-day training activity was completed. This granted the opportunity to search for 3-D models and related documentation and study the virtual representation of different car models and their parts.

The ATS CM4D software (ATS Global, n.d.) has been utilized to analyze different parts and validate statements concerning problematic areas. CM4D functions as a database of cars produced and their measurements taken during running production. This data can be analyzed with product quality in mind and observe whether the cars deviate from expected outcomes. Figure 3.5 illustrates some of the final demand points between the body lamp and car body of the V60.

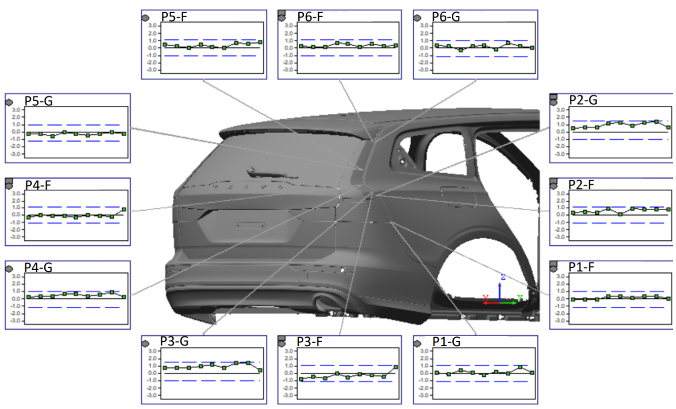

Figure 3.5: Example picture of measurement data on the final demands, retrieved from CM4D.

The figure is slightly modified, and some information has been excluded.

3.2.5 Test Methodology

The following section will explain the methodology used during different tests. Firstly, the common procedure and then the explanations about the test scenarios are to be found in their respective subheadings. The test was conducted to link the causes determined in the fishbone diagram, see Figure 6.1, to MC.

Common Procedure

All tests pertaining to this thesis were carried out in the measuring facilities at Volvo Torslanda. Based on previous observations in the assembly line and discussions within the RDE group, see section 4.4, the V60 body lamp was ruled as a good candidate to perform tests. This part has a well-defined position system, close to the optimal 3-2-1 system, and was deemed to be an easy assembly with repeatability in mind. At the same time, the complex shape makes it sensitive and prone to display deviations as well. Prior to testing, both participants got initial training by the experts at the "measuring room." Each test was conducted five times to have enough samples to draw simple conclusions and be time-efficient as well. To rule out deviations caused by different components, the same car body and body lamp were used. The assembly procedure was altered based on the test conducted, and unlike the PII, the fasteners were only hand-tightened to prevent plastic deformations on the car body. This decision was based on knowledge gained from previously conducted tests within VCC, in which the car body was seen protruding when using the same torque as the PII, see Figure 3.6.

Figure 3.6: Plastic deformation on the car body. Observe the edge closest to the nut sticking out from the flat surface.

The same twelve measuring points, based on the final demand, were assessed during each test, see Figure 3.7. As an example, P1 denotes point 1 and G and F indicate whether the measurement is a gap or flush. The points are located on the body side and, depending on the measuring technique, measured in different manners.

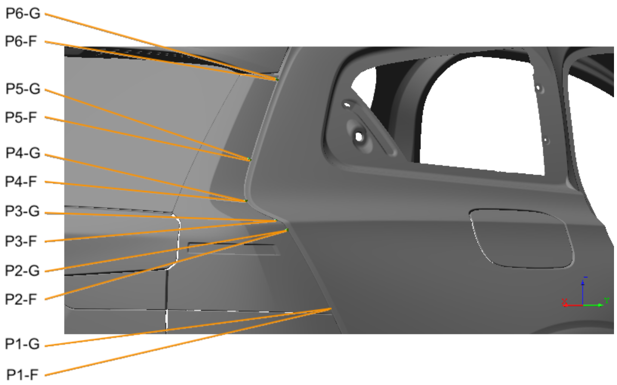

Figure 3.7: Final demand measuring points used during the tests.

The points were measured out and marked on the car body to ensure repeatable measurements. Two different types of measurements were taken, namely gap and flush. Gaps were measured as the width of the split line and flush were measured as the distance between the surfaces relative position, see Figure 3.8.

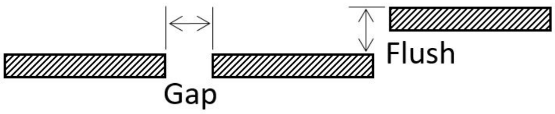

Figure 3.8: Highlighting the gap and flush measures.

The gap measures were obtained using different blades ranging between 0.8-4.0 [mm] in thickness with an accuracy of 0.1 [mm], see Figure 3.9. The flush measures were gathered with a flush gauge, see Figure 3.10.

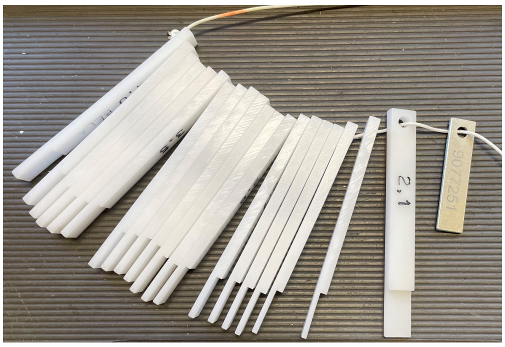

Figure 3.9: Gap pins utilized during the tests.

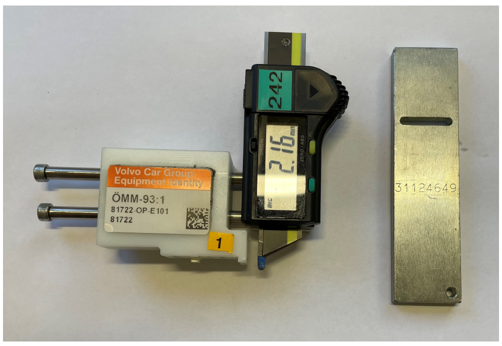

Figure 3.10: Flush gauge together with a reference block.

Per the final demands, the gaps between the car body and the body lamp were taken with the body as a guiding plane. The flush measures used the body lamp as the base and contour of the same as guiding. The flush gauge was adjusted according to the present gap to rule out the gap dependency. Not accounting for the current gap could influence the data and produce faulty measures. All results were noted down in an excel sheet, and the most interesting ones were plotted in a graph using Matlab to give a better representation.

Measurement Capability Test

The first initial test was conducted using the method available for checking measurement capability in the measuring room at VCC. This method was utilized to evaluate the measuring and locating technique and compare the participants' capability to ensure repeatability and reproducibility of measurements and minimize the risk of deviations due to differences in measuring style. The two participants measured the same assembly trial, and the results of the measurements were compared. Further, only the flush measurements were taken into consideration due to these being the most sensitive to inequalities in measuring technique. As per the method, the measuring capability percentage was deemed acceptable if it was below 10% or at least less than 30 % depending on circumstances. All measures with a capability percentage higher than 30% would be regarded as non-approved.

Human Error Contribution Test

To observe how significant the assembly variations between two different operators are, an assembly test was performed on the V60 body lamp. The two operators conducted five trials each of assembling the body lamp on the body of the V60, and gap and flush measurements were taken for each of the final demand measuring points. First, the mean of the measurements was calculated, and then the difference between operator A and operator B was assessed. The outcomes of the test are presented in detail in section 5.2.2.

Tolerance Test

The tolerance test aimed to see whether variation in the manual assembly process could be connected to the tolerances and if this variation could lead to MC. Exploiting the play between the upper pin and the slotted hole, see Figure 3.11, enabled two different test cases to be studied, pushing in (PI) and pushing out (PO).

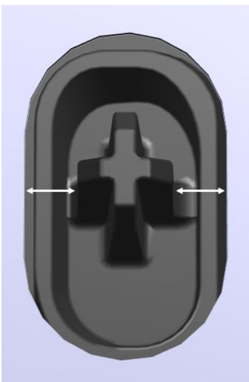

Figure 3.11: Representative picture highlighting, with white arrows, a play between a slotted hole and a plastic pin.

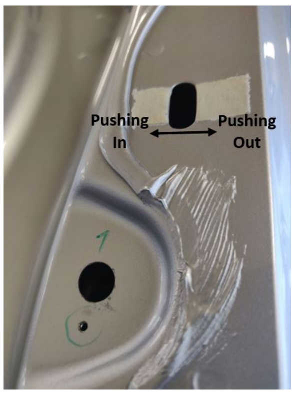

Figure 3.12: Image depicting the tape applied to the slotted hole on the body in white.

The particular body lamp tested had a pin thickness of 7.88 [mm], and the width of the slotted hole was 8.11 [mm], making for a 0.23 [mm] difference, by which the part was allowed to move in and out. Due to the fact, the participants were pushing the lamp in the y-direction, only flush measures were taken into consideration as they were the most influenced in the given direction. One additional test scenario was made to strengthen the pre-assumption of the play between the pin and the slotted hole influencing the outcome. These tests were conducted by removing the play using four pieces of tape, two on either side. By doing this, the slotted hole became approximately 7.85 [mm] wide, delimiting the possibility to move the lamp in and out, see Figure 3.12. Nevertheless, the same procedure as the previous tolerance test was utilized, and the results were compared.

Screw Sequence Test

The changing of screw sequence test was carried out on the V60 body lamp to study the importance of following the assembly sequence and ultimately the influence of changing the location scheme. The two cases compared to one another were the predefined standard 3-2-1 case of assembly, for this experiment named Outer-Top-Inner (OTI) following the screw order and the expected worst-case scenario, referred to as the Inner-Top-Outer (ITO) case. This was thought to be the worst-case since this allows for maximum movement of the lamp since the oversized hole now will functioning as a fully-steering one and vice versa. The current setup of locators on the body lamp of the V60 is shown in Figure 3.13. These locators will be mentioned as inner, outer, and top based on their location.

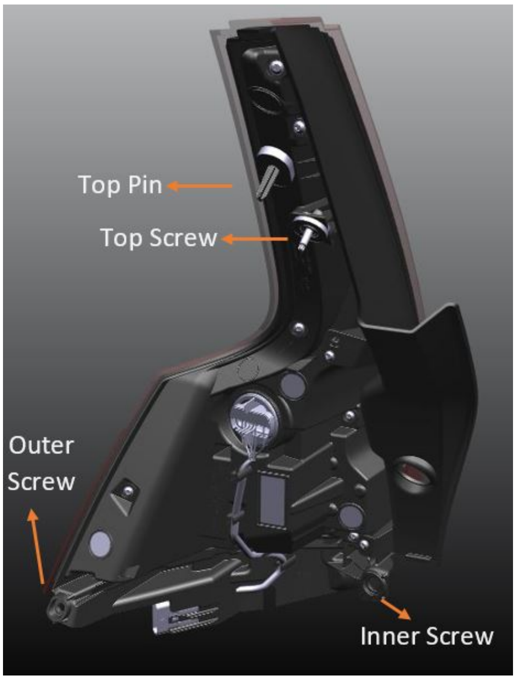

Figure 3.13: Locators on the V60 body lamp.

The final test case was the Top-Inner-Outer (TIO) test case. Again, the screw sequence was changed depending on the test case. For instance, the TIO test started with fastening the top screw, followed by the inner screw, and finally, the outer screw. This test case proved to be an exception in terms of being able to take measures and is reflected in detail under Section 5.2.4.

3.3 Root Cause Analysis

Root Cause Analysis (RCA) is a structured way of identifying the primary causes of problems and analyzing the issue at hand. In this thesis, RCA was performed using the fishbone diagram. The fishbone diagram analysis helps establish the cause and effect relationship in cases where the stakeholder would like to observe the different contributing factors to a problem so that an effective solution can be generated (Coghlan & Brydon-Miller, 2014). In this thesis project, brainstorming, observational studies, case studies, interviews, and test results were used to narrow down the most potential causes and sub-causes, with MC being the problem dealt with at hand. The preliminary version of the fishbone diagram developed in connection to this thesis is shown below in Figure 3.14.

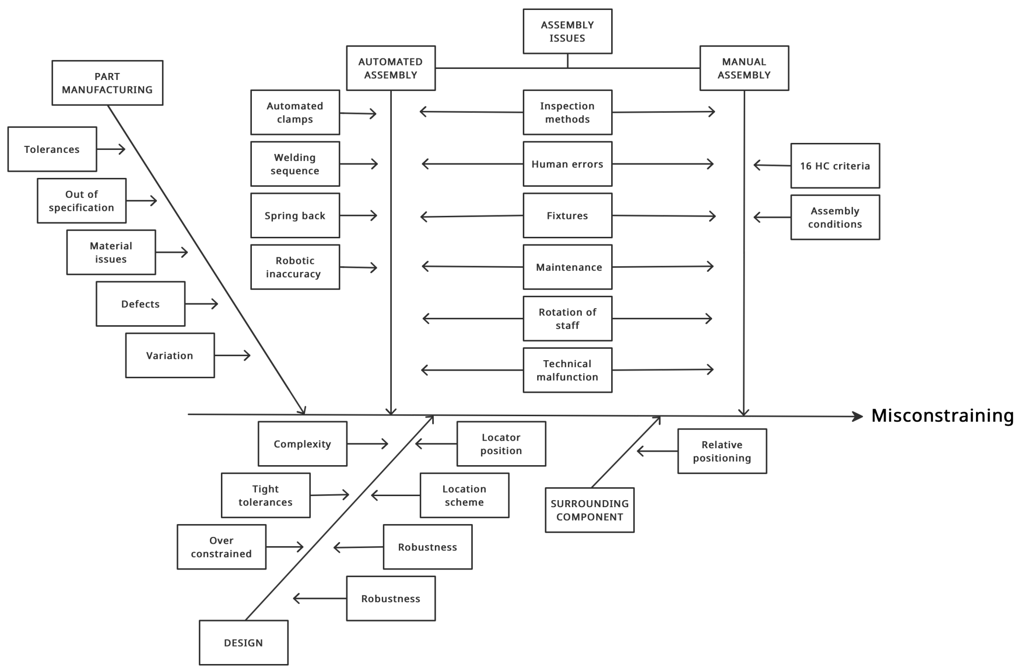

Figure 3.14: Initial iteration of the Fishbone diagram.

As far as this initial iteration of the fishbone diagram is concerned, it was driven by the discussions conducted with the Robust Design Engineering (RDE) team at VCC, literature study and its influence, and initial intuition about this novel concept. This version of the fishbone set the base for further development and enhancement. The fishbone was further iterated using the test results and case studies that will be discussed in the further chapters to come. The fully finished fishbone diagram is presented in Figure 6.1.

4

Industrial Case Studies and Observations

This chapter explains the various case studies analyzed in connection to misconstraining (MC) in the manual assembly process at VCC. To give an industrial perspective on MC, interviews within VCC were also held concerning these case studies. The interviews were conducted with different VCC employees, mainly in GA, to acquire knowledge regarding actual cases of MC that have occurred during production and assembly. The key takeaways from the interviews and observational studies about each case study are summarized and presented in this Chapter. Due to confidentiality issues, the case studies have been presented with a generic mention of the component being tested, with no specific mention made regarding the car models.

4.1 Case Study 1: Novel Body Lamp

During one of the interviews, it was uncovered that exploiting a new solution as a locator led to variation during the manual assembly. The following case study elaborates on the issues leading up to MC.

4.1.1 Background

Technology advancement initiatives enable the elimination of problematic parts, meanwhile stimulates engineers to develop new solutions. This was encountered while VCC was fully incorporating LED technology in the body lamp. Moving to LED allowed for eliminating the ventilation hole between the lamp and car body. Removing the hole and relocating the lamps' electronic connections granted the opportunity to eliminate big and problematic sealings. However, this change required a new solution to the assembly demand of having a third hand, meaning a solution that holds the part in place before torquing the screw connections during manual assembly. Since the previously utilized third hand for assemblies in the X-direction was located in the removed hole, the need for a new solution appeared. Furthermore, this part of the car was non-accessible, eliminating the possibility of using standard fasteners. A plastic ball stud joined with a rubber coupling, known as a snap-lock system, was used, see Figure 4.1. The new solution relied on utilizing the fully guiding locator as a third hand, meanwhile locating as per definition, in this case locating the lamp in X1, Y1, and Z1, see Figure 4.2.

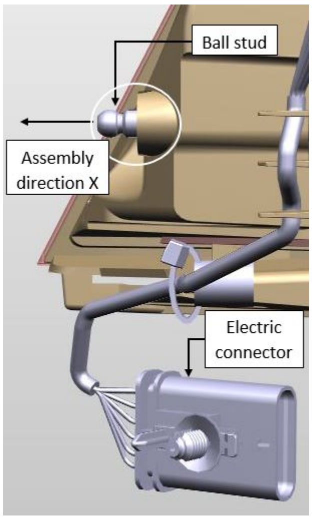

Figure 4.1: The new solution using a ball stud as the third hand.

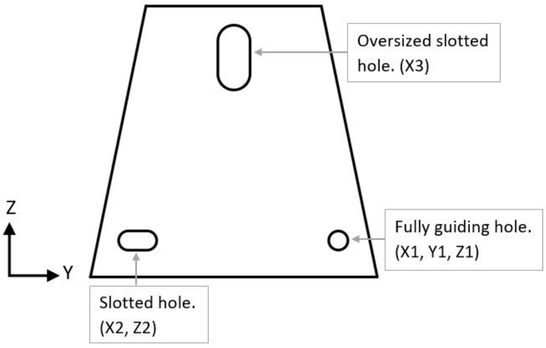

Figure 4.2: Resembles the locating scheme seen on the Body In White.

Besides the snap-lock system, the lamp also relied on a screw fixation guided by a slotted hole, locating the lamp in X2 and Z2. Lastly, the oversized slotted hole positioned at the top of the Body In White (BIW) was designed to locate the lamp in X3 by another screw connection. See Figure 4.2 for an elaborated view of a representative picture of the location scheme.

4.1.2 Occurrence of Misconstraining

The supplier ensured that the new solution would function as a fully guiding reference. Still, it was later discovered that the rubber coupling was too soft, contributing to the variation. The softness and flexibility of the rubber made it possible to assemble the lamp in different positions by pushing it in different directions, hence not locating it as intended.

Moreover, an additional issue was discovered in the oversized upper slot designed to locate the part in the X-direction. A late change was made during development, in which this slot was used both in the assembly of the BIW and as a locator for the lamp. Since the pins used for guiding body parts while assembling are thicker by standard, the slot was redesigned to take the added thickness into account. Unfortunately, this change was done without sharing the information with the team responsible for the positioning of the lamp, ultimately affecting the lamps' robustness. As communicated by the interviewee:

> *"The upper slotted hole became too big, and the change was made very late without us knowing about it."*

The wider hole made the x-plane of the body lamp cut into the edges of the slot during assembly, consequently damaging the plastic material, see Figure 4.3.

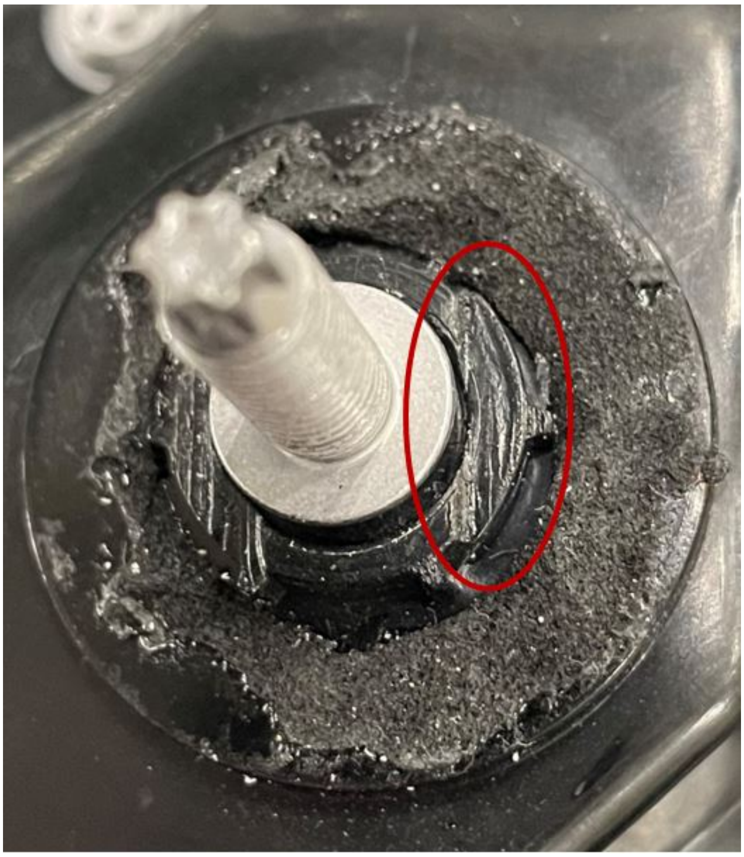

Figure 4.3: The damaged X reference. Note the vertical lines closest to the screw highlighted by the red oval.

The damaged x-plane influenced the predefined reference system and thereby contributed to variation. Both issues lead to the part deviating from the nominal values and together made the part misconstrained. In addition to previously mentioned issues, it was also observed that the lower inner locator was guiding on the screw threads. This situation may cause an inconsistent play between the screw and slot, indeed an issue that could have influenced the robustness of the assembly.

4.2 Case Study 2: The Dual Snap Lock Solution

The dual snap lock system is a novel concept that is being tested as a research study, in this case, to be utilized as a mounting solution in the future. This research study also aims to provide more in-depth knowledge on the snap locks to make more informed decisions moving forward.

4.2.1 Background

A reason behind the affinity shown towards the snap locks is the ease of assembly. The workers can easily plug in the male ball joints protruding from the component onto the female rubber coupling that is present on the sheet metal of the body, see

Figure 4.4. Also, the snap-lock solution is simple and provides higher design freedom with just two components involved.

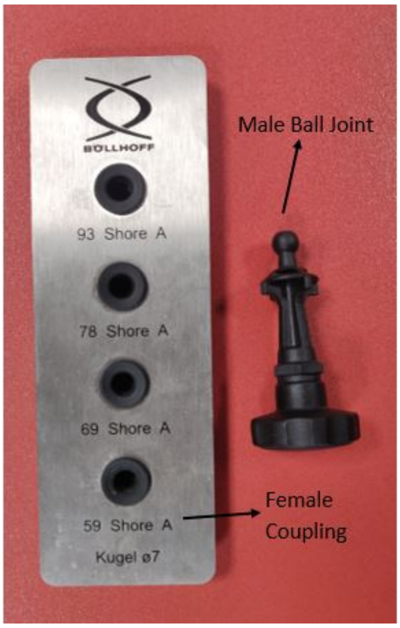

Figure 4.4: A sample template showcasing the male ball joint and the female coupling of different shore hardness values.

Locating Scheme Setup

The planned locating scheme for the research study was an over-constrained 4-2-1 system defined in X, Y, and Z directions, respectively. As shown in Figure 4.5, X1 and X2 references are provided by the screw fixations, and the snap locks provide the remaining X3 and X4 references. In addition, there are two pins on the intended component, among which the pin on the top lands on a perfectly sized hole and gives referencing in the Y1 and Z directions, whereas the bottom pin seats in a slot and provides the referencing in the Y2 direction as shown in Figure 4.5. Concerning the two rubber couplings, a member of the RDE team had the following comment about the reason behind the choice of rubber in this case.

> *"It was predicted that two soft rubbers would act together as one hard rubber snap lock and provide the required X referencing and a third hand."*

Verification of the Dual Snap Lock Solution

There were concerns about the rubber on the coupling's inability to handle the calculated or expected variation of 1.5 [mm] in the Y direction. Also, the snap locks would be providing additional guidance in the Z direction, affecting the positioning of the intended component. To verify the rubber's behavior towards variation and its performance when the mounting points on the body were slightly shifted from their planned position, a test rig was developed by the personnel in the measurement room at VCC. Figure 4.5 below presents the rig, the mounting plates, and snap locks used for the test.

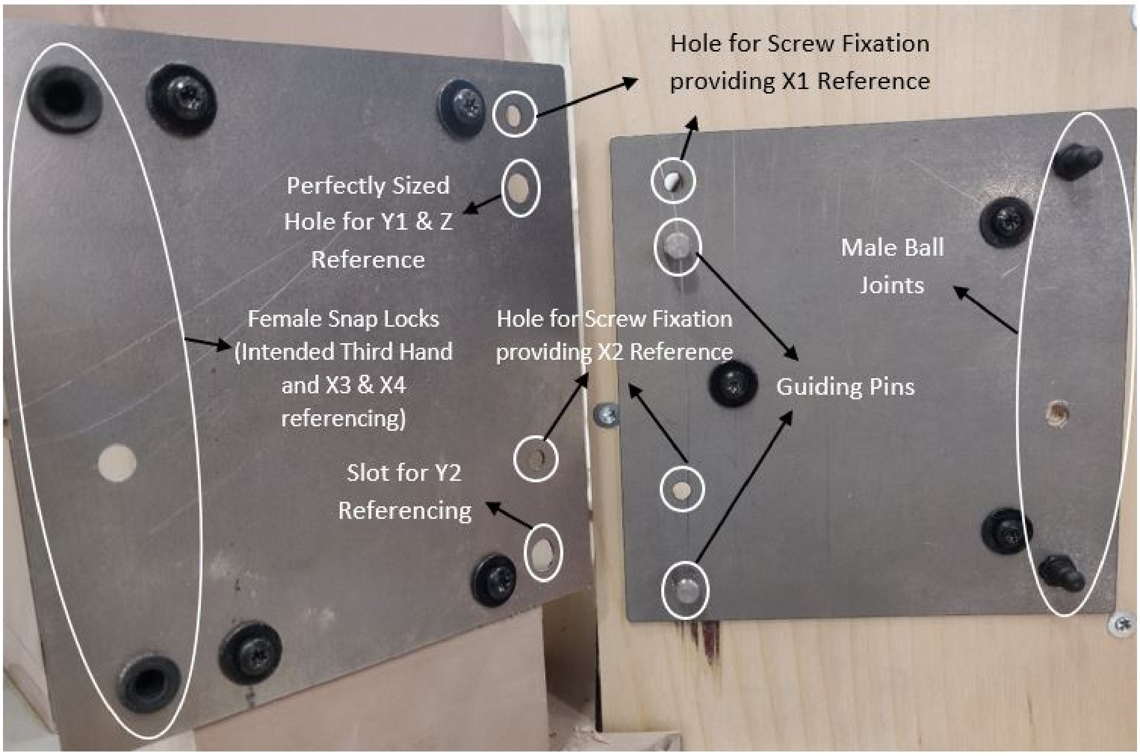

Figure 4.5: Test rig developed for experimenting the behaviour of the snap locks.

4.2.2 Occurrence of Misconstraining

As the first step in the testing process, the snap-lock was slightly shifted from its planned position to resemble the variation, and then the assembly of the intended component was performed. Performed by two Manufacturing Engineering (ME) employees, the test exposed areas of concern that had to be resolved before moving forward with this dual snap lock solution. As mentioned by one of the test engineers:

> *"Even after the shift in the snap lock position, it was possible to mount the component, but the snap-lock was no longer providing the intended third hand as the component showed signs of falling away. The reliability of the proposed concept is questionable."*

From the test results and brainstorming around the concept of MC, it was decided at the end of this research study that the idea of using dual snap locks would not work out and would under-perform. Eventually, a decision to remove the snap locks and proceed with a simple screw and nut fastening system on the body side was taken as shown in Figure 4.6. Misconstraining, in this case, was suspected to happen, and this research study helped discover the potentially problematic areas with the dual snap lock solution and carry out a change to prevent MC moving forward.

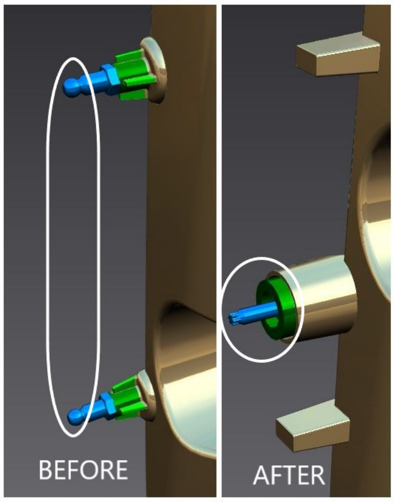

Figure 4.6: Before and after comparisons showing the change in mounting solutions.

4.3 Case Study 3: Sill Moulding Case

The sill moulding is a carryover part utilized by different car models produced in various plants. This case study is about the problems uncovered during the manual assembly process that led to MC.

4.3.1 Background

The sill moulding is a long yet stable component located on the body side, see Figure 4.7. Nevertheless, it is prone to twist around the X-axis and, therefore, is designed with an over-constrained reference system to handle forces and make it sit secure against the body.

Figure 4.7: Highlights the sill moulding and its location together with the investigated area.

Problems started to appear in the section where the sill moulding meets the body-side. This was observed on the assembly line under normal production. The investigated area shown in Figure 4.7 was deviating from the geometrical requirements and tended to produce gap and flush measurements that deviated away from the nominal values.

4.3.2 Occurrence of Misconstraining

While the part-responsible engineer and the robust design engineer observed the assembly line, they discovered that one assembly worker was applying force right between two clip fasteners in the back part of the sill moulding. These clip fasteners and their mating did not provide a stoppage in the assembly - /y-direction, enabling the part to flex. This ended up damaging the x-reference in the back and fixating it in an unintended position, see Figure 4.8, hence making the part deviate from the final demands and produced measures that deviated away from the nominal, see Figure 4.9.

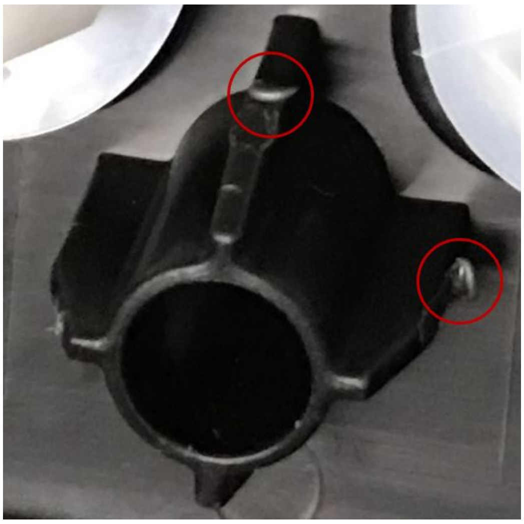

Figure 4.8: Sill moulding X-reference. Notice the small indents in the black guiding pin highlighted by red circles.

Figure 4.9: Gap and flush measure further away from the nominal than anticipated.

The cause of the issue is partly to blame the manual assembly process and that the workers were not following the instructions, as stated by the interviewee during the session:

> *"You are not in a hurry while doing the verification prototype build. It is first in mass production [. . .] people take shortcuts."*

However, the Process Inspection Instruction (PII) gave insufficient guidance that the workers could interpret in numerous ways. Therefore, the PII for this specific part assembly has currently been redefined to account for the potential shortcuts and provides more detailed instructions on where to engage the clips.

4.4 Observational Study: Factory Visits and Body Lamp Refitting

Having visited the factory floor on a limited number of occasions, the following section presents a summary of situations that were either observed or discovered through discussions with the ME executives accompanying the factory visit and workers on the factory floor. The manual assembly operation is carried out in the C-shop at VCC and this is where the majority of the observations were made.

4.4.1 Observational Study 1

The rear body lamp has been described as a problematic area concerning geometrical variation, especially concerning the right-hand side. Enlightened by preliminary discussions in the RDE team and talking with assembly workers, a careful examination of the rear end was performed on the factory floor. It was uncovered that the lamps were attached during the beginning stage in one of the assembly lines in the C-shop, and screws were tightened in the last stage in the same section of the line. This discovery led to further studying the PII to ensure that the assembly followed the described procedure. According to the PII, the body lamp assembly was supposed to be conducted in one sequence, but changes were made on the factory floor to balance the workstation time.

4.4.2 Observational Study 2

Another situation that caught the eye was during the observational visit within the C-shop accompanied by a ME executive. There is a specific section of the assembly line where the tailgates are refitted to ensure that they are centered and are in line with the gap measures required with the body lamp. Having observed a tailgate adjustment in one of the car variants, there was a sudden instance where the assembly worker, instead of refitting the tailgate, went ahead and refitted the inner screw of the body lamp. This meant that the body lamp that had been torqued as per specification in a previous section was now unfastened and refitted to satisfy the gap measure. This is what the ME executive also mentioned when asked about

> *"Since it is easy to influence the body lamps, some workers refit the inner screw instead of spending time refitting the tailgate position. However, VCC takes great care in ensuring that it does not happen in most cases."*

4.4.3 Observational Study 3

Furthermore, the problematic and complex assembly of fitting the tailgate to the body was shown. This was described to be problematic both in the A- and C-shop. Both depend on fixtures, which could cause problems due to the lack of maintenance of the shims controlling the placement. Moreover, the human side of not putting the parts correctly onto the fixtures could also contribute to variation. While observing the assembly in C-shop, it was uncovered that the procedure also utilized dummy fixtures to resemble the body lamp to place the tailgate. A final comment made by the ME executive in connection to issues with fixture placements was:

> *"These fixtures could either be set incorrectly by the assembly worker, or the welds on the car body, being too big, could interfere with the fixture placement."*

5

Results

This chapter will explain the various test results obtained in connection to Misconstraining (MC) and a detailed analysis of the results. To analyze is to look beyond numbers and statements wherein the true essence of the problem being dealt with is obtained. The procedure followed for each of these tests has already been elucidated in Section 3.2.5. In the due process of collecting these results, many findings that are out of scope concerning this thesis were identified and will be treated as information for further research to be carried out.

5.1 Analysis of Production Data

Some interesting cases of variation were discovered by analyzing production data in CM4D. Figure 5.1 is showcasing the gap final demand point number 3 (P3-G), see Figure 3.7. The figure utilizes data taken from 50 different cars produced and sampled for approximately one and a half years. However, information about tolerance limits and variation allowed has been excluded due to confidentiality.

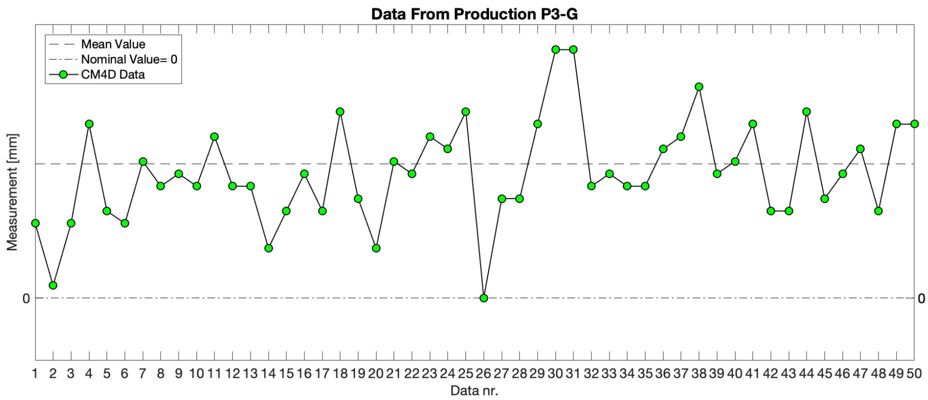

Figure 5.1: Results from CM4D investigation of the gap measuring point (P3-G).

Figure 5.1 indicates a variation between the measured cars. The mean shift is especially interesting, being rather far away from the nominal value. The graph shows some fluctuating tendencies and highlights that the body lamp, the car body, or the assembly contribute to the variation. Therefore, the body lamp was selected as an ideal specimen to investigate whether MC could be the source of the variation mentioned above.

5.2 Test results

The following section contains the results retrieved during various test cases trying to connect known problems to MC. Furthermore, comments have been provided, highlighting the prominent inferences from each of the test cases.

5.2.1 Measurement Capability Test

The measurement capability test was conducted to assess worker proficiency and see whether the measurements could vary between the participants. The measuring capability between the two participants showed rather significant differences, see in Appendix F.1, especially concerning measuring points P2-F, P3-F, and P5-F, shown in Figure 3.7, since these measures received a capability percentage over the allowed 30%. Although the tolerance range (T) does not correspond to the actual range for the given point, it is given to exemplify the calculation. Based on the capability study, it was decided to have one participant responsible for each measuring technique to minimize the risk of influencing the results. As a result, the variation in taking measures can be neglected. Table 5.1 illustrates how the compatibility percentage is calculated at VCC through values obtained for demand point 2 (P2-F), which was found to be problematic, as mentioned above. The table presents the measurements taken by the operators as 'Op A' and 'Op B' with the difference in between them presented as 'RA-B'.

Table 5.1: Capability test results for demand point P2-F.

	Op A	Op B	RA-B
1	1.21	1.29	0.08
2	1.28	1.42	0.14
3	1.27	1.44	0.17
4	1.21	1.41	0.20
5	1.23	1.42	0.19
Variation R	$\frac{\Sigma R}{5}$	$\frac{0.78}{5}$	0.156
Tolerance range, T	T =	±1	2
Capability C	$\frac{R \cdot 4.33 \cdot 100}{\mathrm{T}}$		33.8

5.2.2 Human Error Contribution Test

The purpose of the human error contribution test was to study if people's different prerequisites could cause variation and potentially contribute to MC. Both operators assembled the body lamp five times, and every one of the final demand points was measured during each trial. Following the methodology set up for this particular test, the set of measurements obtained are shown in Appendix F.2. As shown in Table 5.2, the demand points 2 and 3 were sensitive to the change in operators and showed the highest difference in gap and flush measurements. This is in line with the theory that the points away from the locators are less robust and are susceptible to geometric variation (Söderberg et al., 2016).

Table 5.2: Human error contribution test tabulation.

Unit [mm]	P2-G	P3-F	P3-G	P4-G
Mean A	2.680	-2.584	2.600	1.660
Mean B	2.220	-2.358	2.060	1.380
Difference	0.460	0.226	0.540	0.280

From the mean value of gap and flush measurements, it can be seen that the difference in measurements between operator A and B are the highest for measures P2-G, P3-F, P3-G, and P4-G, highlighted in Table 5.2.

5.2.3 Tolerance Test

The tolerance test aimed at investigating if tolerances could influence variation in the assembly line. The results indicated that none of the measurements were far away from the nominal value, see Appendix F.3. Nevertheless, the difference between the two test cases, without and with tape, especially concerning flush measuring point number four can be seen as interesting, see Figure 5.2 and 5.3. The figure shows the Pushing In (PI) as the blue line and Pushing Out (PO) as the red line, and the nominal value is also indicated with a dashed black line.

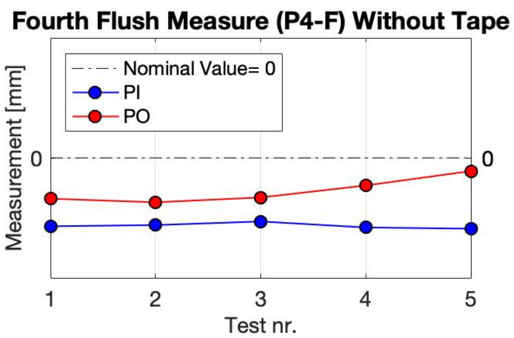

Figure 5.2: Results from the fourth flush measure in the tolerance study for the without tape case.

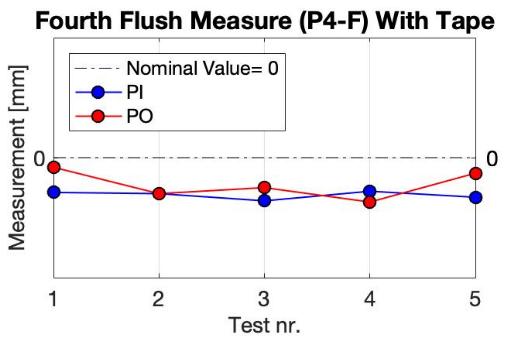

Figure 5.3: Results from the fourth flush measure in the tolerance study for the with tape case.

The difference between the two test cases might not be much in comparison to the nominal value. However, the deviation tendencies are still essential to evaluate. Table 5.3 presents the mean difference between the two test cases and the corresponding measuring point.

Table 5.3: Absolute mean difference of the flush-measures between PI and PO, taken during the tolerance test.

Unit [mm]	P1-F	P2-F	P3-F	P4-F	P5-F	P6-F
Mean PI	-0.726	-1.320	-2.542	-1.866	-1.162	-0.750
Mean PO	-0.776	-1.288	-2.350	-1.576	-0.910	-0.546
Difference	0.050	0.032	0.192	0.290	0.252	0.204

The test result conveys that the measuring points P4-F and P5-F allowed more movement than the difference in dimension between the pin and the slotted hole, being 0.23 [mm], as observed on the tested parts. The following results, as seen in Table 5.4, were produced by removing the play between the pin and the slotted hole using tape.

Table 5.4: Absolute mean difference of the flush-measures between PI and PO, taken during the tolerance test with added tape to remove the play.

Unit [mm]	P1-F	P2-F	P3-F	P4-F	P5-F	P6-F
Mean PI	-0.940	-1.640	-2.440	-1.612	-1.306	-0.792
Mean PO	-1.000	-1.616	-2.372	-1.526	-1.138	-0.722
Difference	0.060	0.024	0.068	0.086	0.168	0.070

By comparing the absolute difference between PI and PO gathered in the two test scenarios, it can be seen that the addition of the tape resulted in a smaller spread in between the flush measures. This indicates that the case with the tape is a more stable output solution when compared to the one without tape. The overall percentage reduction in the difference between the flush measures for both cases is presented in Table 5.5. Notice that the variation in most of the measures reduces by adding tape.

Table 5.5: Percentage change in difference between the flush measures of the 'without tape' and 'with tape' cases.

Unit [mm]	P1-F	P2-F	P3-F	P4-F	P5-F	P6-F
Difference without tape	0.050	0.032	0.192	0.290	0.252	0.204
Difference with tape	0.060	0.024	0.068	0.086	0.168	0.070
Percentage change in difference	**20%**	**-25%**	**-64.6%**	**-70.3%**	**-33.3%**	**-65.7%**

Phase Two Tolerance Test

A preliminary indication concerning the with tape and without tape test cases were obtained through the five trials mentioned above. However, to increase statistical accuracy, the same test was performed once again as a phase two tolerance test with ten trials for each of the test cases as shown in Appendix F.4. Once again, this new set of trials indicated that the 'with tape' test case is more stable when compared to the 'without tape' test case, highlighted by flush point number six in Figure 5.4. Furthermore, as shown in the image, there is consistency among the measurements in the 'with tape' test case denoted by the two red lines in the middle compared to the 'without tape' test case represented by blue lines, which fluctuated a lot over the various trials conducted. The lines at the top of the figure correspond to the PO cases, and the lines at the bottom feature the PI cases.

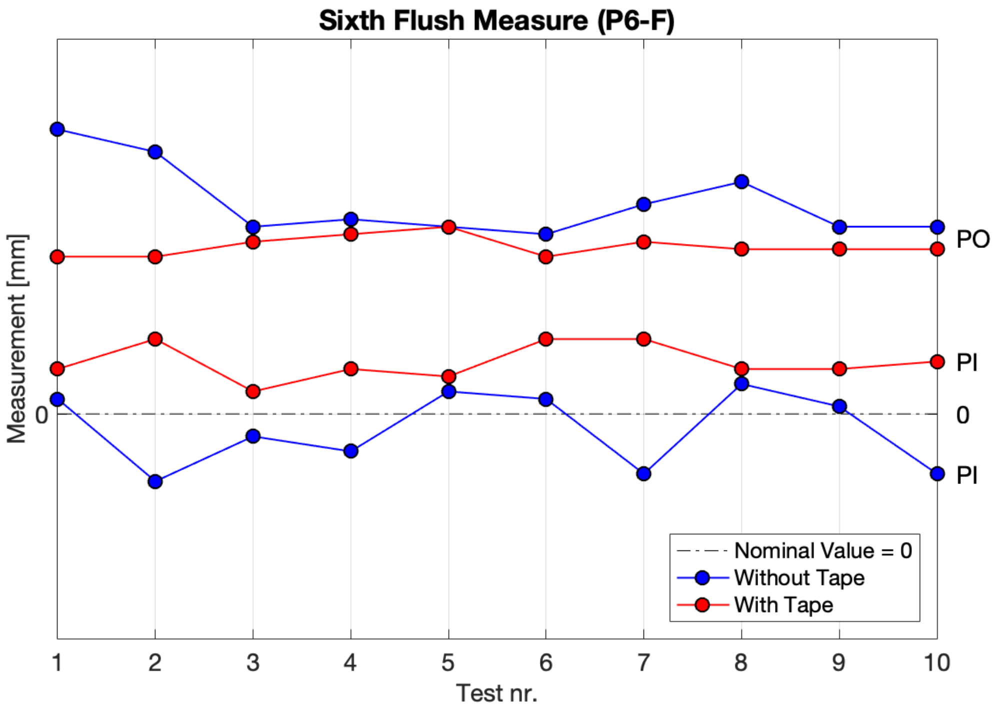

Figure 5.4: Results from the sixth flush measure in the phase 2 tolerance study. An indication of whether the lines resemble the PO or PI case is found on the far right side.

Furthermore, this result strengthens the hypothesis that was shaping up in the previous five sample trials. The absolute mean difference of the flush measures between the PI and PO for both the test cases is presented below in Tables 5.6 and 5.7.

Table 5.6: Absolute mean difference of the flush-measures between PI and PO for the without tape case, taken during the phase 2 tolerance test

Unit [mm]	P1-F	P2-F	P3-F	P4-F	P5-F	P6-F
Mean PI	-0.635	-1.049	-2.007	-1.200	-0.606	-0.921
Mean PO	-0.565	-0.901	-1.813	-1.032	-0.346	-0.618
Difference	**0.070**	**0.148**	**0.194**	**0.168**	**0.260**	**0.303**

Table 5.7: Absolute mean difference of the flush-measures between PI and PO for the with tape case, taken during the phase 2 tolerance test.

Unit [mm]	P1-F	P2-F	P3-F	P4-F	P5-F	P6-F
Mean PI	-0.570	-1.027	-2.082	-1.348	-0.719	-0.831
Mean PO	-0.536	-0.971	-2.015	-1.209	-0.544	-0.676
Difference	**0.034**	**0.056**	**0.067**	**0.139**	**0.175**	**0.155**

Similar to the test results obtained in the first 5 sample trials, there was a decrease in the absolute difference between the flush measures in the ‘with tape’ test case compared to the ‘without tape’ case. However, since the addition of the tape was onto the top slot on the car body, the two closest points, P-5 and P-6, are more likely to be influenced and hence will be the only measures analyzed here. The difference between the mean of the measures of PO and PI for these points in the ‘without tape’ case compared to the ‘with tape’ case produced the following results as shown in Table 5.8.

Table 5.8: Percentage change in difference between the flush measures of the without tape and with tape cases.

Unit [mm]	P5-F	P6-F
Difference without tape	0.260	0.303
Difference with tape	0.175	0.155
Percentage change in difference	**-33%**	**-49%**

Overall, the tolerance tests indicated that tape in the second case limited the natural rattle or play between the pin and the slotted hole. As a result, it was possible to arrest the fluctuation in measurement values and produce a more stable solution. In this test case, the variation seen in Table 5.7 is variation solely due to the system involvement as the assembly influence was removed using the tape. Also, with the presence of the tape, the system is improving as a whole with a decrease in variation across all flush points. This is likely an indication of higher robustness or reduced geometric variation when the play between the pin and the slot in the guiding direction was limited to almost close to zero. The notion about reduced geometric variation leading to increased robustness is similar to what was expressed by Mashhadi, Alänge, and Roos (2012).

Further analyzing the test results, it can be seen from the mean difference tabulation shown in Table 5.6 that the body lamp was rattling in points P5-F and P6-F more than the measured difference between the pin and the slot in the ‘without tape’ case. This potentially reflects the fact that the pin being made in plastic is flexing or bending under the application of the inward or outward forces during assembly, or this could also be due to measurement inaccuracy which will be further discussed in Section 6.5.2.

5.2.4 Screw Sequence Test

The screw sequence test aimed to examine the importance of following the predefined assembly sequence. The results indicated that changing the screw sequence to something other than the intended will influence the outcome. The two measuring points mainly influenced by the changing of screw order were the flush measure number one (P1-F) and the gap measure number three (P3-G), see Figure 3.7. The results from the two different test scenarios, OTI and ITO, are indicated with a blue and red line, respectively, and can be seen in Figure 5.5 and 5.6 for the two measuring points. The nominal value is indicated with a black dashed line.

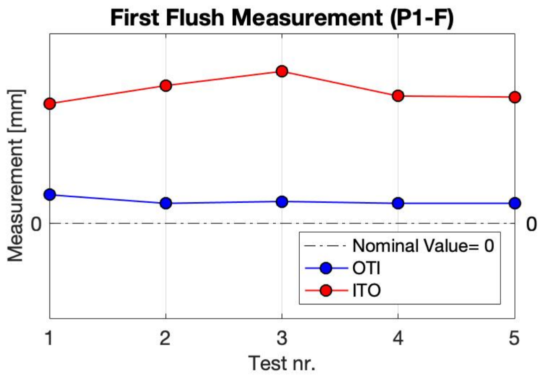

Figure 5.5: Results from flush measure number 1. The two test cases, OTI and ITO are indicated with blue and red lines.

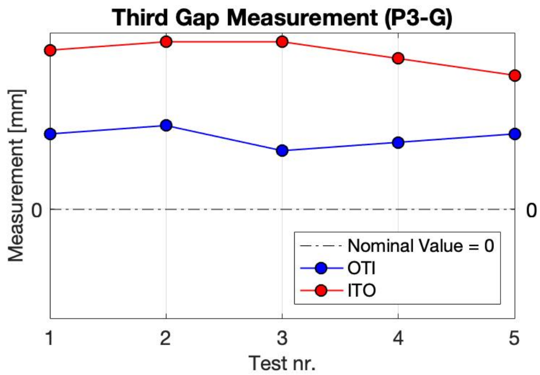

Figure 5.6: Results from gap measure number 3. The two test cases, OTI and ITO are indicated with blue and red lines.

Figure 5.5 is highlighting the first flush measuring point (P1-F), being the closest to the outer fully guiding hole. This point was shown to be sensitive to the sequence change, whereas all five flush measurements in the ITO case were further away from the nominal value when compared to the OTI case. In addition, the results from the gap measure number three (P3-G), shown in Figure 5.6, was also indicating sensitivity. A complete set of all measuring points can be found in Appendix F.5. Additionally, the shift of the screw sequence affected the overall system. It caused a miss-alignment of the fully-steering hole (Outer Screw) and its mating as shown in Figure 5.7.

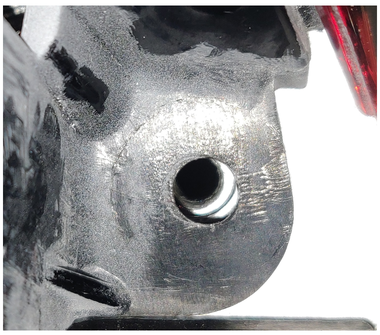

Figure 5.7: Misalignment of the outer screw obtained as a result of altering the screw sequence.

Top–Inner–Outer Case

The screw sequence was shifted to occur in the order that the top screw mounting was done first, then the inner screw, and finally, the outer screw was fastened. It was observed that in this screw sequence, the top guiding pin was rested on the bottom of the slot instead of remaining suspended in the air. The fastening of the top screw meant that the screw intended to provide just the X guiding was now giving the X, Y, and Z guiding. This ultimately collapsed the positioning for the inner and outer screws and made it impossible for the screws to be mounted in their desired position. The deviation in the outer end was so extreme that it was impossible to take measurements along the defined demand points. Figure 5.8 exhibits the extent to which the red outer shell of the body lamp was deviating from the body of the car.

Figure 5.8: The deviated red outer shell on the body lamp during the Top-Inner-Outer test Case.

6

Discussion and Recommendations

Reflecting on the results obtained and their relevance to misconstraining (MC), this chapter explicates the significance of the results, a checklist containing a list of recommendations, limitations, and experimental uncertainties in the tests conducted, and suggestions for future work to be carried out.

6.1 Mapping the Causes

Utilizing the case studies and test results obtained, the causes of MC were mapped in the form of a fishbone diagram, see Figure 6.1. The causes featured within the red box are outside of the thesis scope. Nevertheless, they are believed to be contributors to MC and are essential for the mapping. Hence, a brief discussion regarding these causes will be presented in the following chapter.

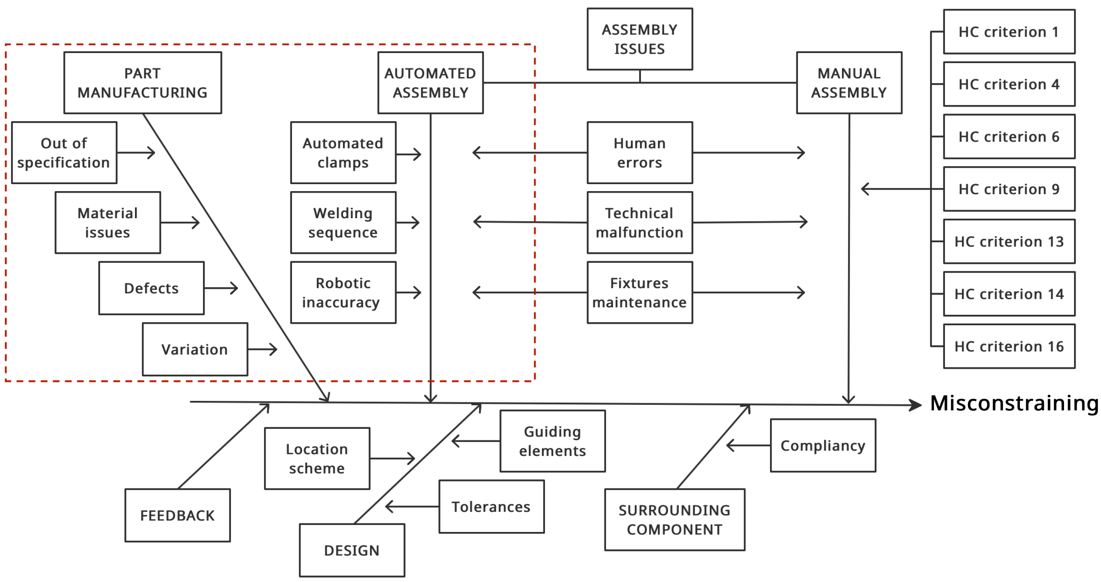

Figure 6.1: Fishbone diagram for Misconstraining.

A detailed explanation of the contributing factors and their connection to MC is presented in the following subsections. With the case studies, observations, and conducted tests as the basis, it was possible to decipher the relevant criteria from the 16 HC criteria list. Hence, HC criteria 1, 4, 6, 9, 13, 14, and 16 have been shortlisted and utilized in this report section. Table 6.1 serves to ease the interpretation of the shortlisted HC criteria and how they are thought to be connected to MC.

Table 6.1: The shortlisted HC criteria based on the research by Falck, Örtengren, et al. (2017a).

1	Many different ways of doing the task
4	No clear mounting position of parts and components
6	Hidden operations
9	Operations must be done in a certain order
13	The geometric environment has great variety (tolerances), i.e. the level of fitting and adjustment varies between the products
14	Need of clear work instructions
16	Lack of (immediate) feedback of properly done work by e.g. a clear click sound and/or compliance with reference points

Nevertheless, it is believed that future studies could make a further linkage between the remaining HC criteria and MC.

6.1.1 Assembly Issues

As shown in Figure 6.1, the factory floor in VCC has both automated assembly and manual assembly in its operational chain. Observing both the processes, a few common causes leading to MC were identified, namely human errors and technical malfunction of the supporting equipment, in addition to the unique contributing causes under each category.

Manual Assembly Issues

All the case studies and the test results together indicated that many of the 16 HC criteria mentioned by Falck, Tarrar, et al. (2017) were contributors to MC. Therefore, the analysis of the manual assembly process was carried out in connection to the shortlisted criterion as mentioned in Table 6.1. The manual assembly process issues are generally related to assembly complexity which can further be broken down into problems originating from poor assembly ergonomics, assembly sequence not being followed, hidden assemblies, etc.

HC Criteria 1, 9 & 14

Starting with criterion 1 as well as criterion 9 and their interpretations as mentioned in Appendix A, the assembly of the body lamp on the car body could be done by following different screw sequences as discussed in Section 5.2.4. However, this attempt to assemble the body lamp in ways other than the standard sequence set by the RDE team at VCC led to a misalignment of the body lamp on the outer screw section, as shown in Figure 5.7. With a significant amount of misalignment, the process of trying to complete the body lamp assembly would have caused MC, as explained in Section 5.2.4. Furthermore, considering criteria 9 and 14 in conjunction, the sill moulding case study mentioned in Section 4.3 is a typical example of the PII not mentioning the assembly sequence in a clear manner. As a result, the assembly workers operating as they saw fit, which eventually led to MC. Overall, the assembly sequence indirectly denoted by the HC criterion 1, 9, and 14 is an essential contributing factor to MC.

HC Criteria 4 & 6

Assessing criteria 4, the importance of having guiding or controlling satisfied throughout the manual assembly process is relatively high. As observed in the novel body lamp case mentioned in Section 4.1, the snap-lock system, which was designed to act as a fully steering reference on the outer side, failed to perform its intended guiding, and hence the system was underconstrained. Also, the slot on the inner side ending up enlarged in size partially contributed to the issue of MC as well. The research study, as mentioned in Section 4.2, is also connected to this criteria since the situation was of an overconstrained system where the snap locks were guiding in a direction they were not designed for in the first place. Simultaneously, criteria 6 also holds suitable for both these case studies since the fitment of the snap-lock system happens away from the line of sight of the assembly workers and hence has a higher level of assembly complexity attached to it. Summarizing both these test cases, it can be seen that criteria 4 and 6 concerning the guiding or referencing system are critical and must be considered concerning MC.

HC Criteria 16

Criteria 16 and its connection to the feedback received while assembling were evident in the V60 body lamp testing case. The top pin, as shown in Figure 3.13 is positioned in a slot, and once placed, there is no feedback received. Therefore, it is impossible to know whether the pin has landed as expected. Depending on whether the pin sits on the bottom of the slot or is suspended in the air, a change in the test results was observed as shown in Section 5.2.4. So there must be some form of feedback that the operator can receive upon positioning the body lamp on the body using the reference pin on top. This case study thus proves the importance of considering criteria 16.

Automated Assembly Issues

The recent advancements in robotics have made it possible to achieve a high level of operational accuracy. However, the loading of the components and the fixtures involved is still something that is handled manually in the A-shop at VCC, see Section 4.4. Upon preliminary discussions with the line managers and the team leads on the factory floor, it was discovered that other than just robotic inaccuracies, factors such as fixture variations and welding deviations primarily contribute to MC. This is similar to the notion expressed by the authors in (Wärmefjord, Söderberg, & Lindkvist, 2016). However, the scope of this thesis is limited to the manual assembly process, and hence the information gathered in connection to automated assembly will be made available to VCC for further research to be carried out.

6.1.2 Human Error

In the manual assembly operation, every assembly worker has a unique style of operation wherein the way they perform tasks is quite different. Therefore, the human touch must be considered even though every operator follows the PII by default. As mentioned by the authors in (Saptari et al., 2015), the correlation between performance and workload is as important as observing the individual error contribution by the assembly workers. Furthermore, referring to Section 5.2.2 the difference in measures between operators A and B on certain demand points were significant. Therefore, even though it is impossible to quantify their contribution to MC, the human error contribution cannot be ruled out of the picture.

6.1.3 Part Manufacturing Issues

Component level errors can have a significant influence on MC in general. This was inferred from the discussions with a geometry engineer on the factory floor in the C-shop at VCC. A snippet from the actual conversation is presented below.

> *"When parts are out of specification, naturally collision or misguiding amongst the surrounding elements or parts happen. This is the part level variation considered in connection to geometrical variation."*

On a macroscopic level, the component variations would not be visible to the naked eye but could still be the major contributor to errors in general. This is because the errors originating at a root level will further influence the operations higher up in the order and present a more significant problem. Interestingly, parts being out of specification are interconnected to the surrounding component issues and are to be dealt with collectively. But at the same time, since the scope of the thesis revolves around the manual assembly operation, the studies conducted about part manufacturing issues will be documented for future research.

6.1.4 Design Issues

As mentioned in Section 2.3.1, Söderberg and Lindkvist (1999) emphasize the importance of having the design as uncoupled as possible. But it is seen that many of the parts studied are by themselves coupled by default. Furthermore, it is also essential to understand that the surrounding components rely on their placement, e.g., the bumper skin partly depends on the body lamp. With this being stated, the perfect uncoupled design is seldom achievable; therefore, parts being miss-constrained might also affect other components. Furthermore, novel design solutions or technical advancements initiatives seem more prone to become miss-constrained due to the lack of knowledge regarding the solution, similar to the case study 1, see Section 4.1.

Tolerances

As highlighted in the theoretical framework, see Section 2.3.3, and by Söderberg et al. (2016), tolerances play an important role in accounting for many types of variation. However, the results from the tolerance test, see Section 3.2.5, conveys that tolerancing also could play a part in causing MC, especially concerning the play between guiding elements and their mating surface. This was highlighted in Table 5.8 in which a percentage decrease in variation among flush measures between the two test cases could be obtained by removing the play, partly caused by the set tolerances.

Location Scheme

The location scheme is one of the key aspects in achieving a robust design, as presented in the theoretical framework, see Section 2.3.2. This was also highlighted by analyzing the results from the change in screw sequence which indirectly influences the location scheme, see Section 5.2.4. The results indicate that changes to the location scheme could influence and be a part of the rise of MC. Figure 5.6 is showcasing this issue; the results produced measurements further away from the nominal values. Additionally, if the design is not supporting the chosen location scheme, issues could lead up to MC, similar to the body lamp case study 4.1. As expressed by the interviewee:

> *"One of the root causes was that the hole was made larger. The X [reference] of the lamp was destroyed due to the larger hole and thereby created variation"*

Guiding Elements and Fasteners

Opting for the correct guiding elements and fasteners is an essential aspect of the industrial process. The selection played a significant part in causing MC in several cases. For example, it was shown in the novel body lamp case, see Section 4.1, that choosing a new type of snap-lock system was one of the leading causes of MC. In the same case study, it was observed that guiding on screw threads could cause variation and contribute to geometrical variation. Furthermore, the sill moulding case, see Section 4.3, emphasizes the influence of not having proper guiding or the lack of it. Even the research study assessing the usage of a dual snap lock system, see Section 4.2, indicated that opting for the right set of fasteners and guiding elements is vital to consider to prevent MC.

6.1.5 Absence of an Effective and Timely Feedback Loop

Feedback is essential to know what went well and what needs improvement to enhance the product development process. The development scope also partially depends on feedback as the drive for further change and improvement comes from the feedback received. Feedback also helps teams at the earlier stages of the product development process to understand the difficulties faced by the manufacturing and assembly departments lower down the product development chain. For example, in the study about the snap-lock solution as mentioned in Section 4.1, there was a situation where the slot was utilized for multiple purposes apart from what it was designed for, and the RDE team was never informed about it. In this case, the feedback or communication lapse meant that the slot lost its functional importance, and MC was the result. Discussing the same with a member of the RDE team, it was clear that the ME team was doing their best to present facts and proof as and when possible during their feedback meetings. But sometimes, the topic's nature makes it hard not to bring subjective opinions onto the discussion. In his own words:

> *"There is a huge scope for improvement here, and it might be beneficial if the ME team performs concurrent testing on the product solutions as they are developed so that quick changes can be made on the go. We need them to be clear, concise, and relevant in what they communicate."*

6.1.6 Surrounding Component Issues

Compliancy is believed to be one of the contributing factors towards MC regarding surrounding components involved in the assembly. A body is subjected to be non-rigid or compliant if it suffers a change in its form or shape upon the application of force, as seen from tests conducted on the V60, see Figure 3.6. For example, in the V60 body lamp testing, the sheet metal onto which the lamp was mounted was 0.8 [mm] thick, as observed in Teamcenter Visualization Mockup. It thereby stimulated the thought about it being compliant. Owing to the relative complexity of the topic and the fact that the study about compliancy would be much broader than the scope of this thesis, a brief discussion on compliancy and suggestions for future work are presented in the conclusions chapter within Section 6.5.5.

6.2 Effects of Misconstraining

This section will explain in detail the effects of MC. It is essential to figure out the effects based on the studies connected to MC so far to understand when and how MC becomes a predicament in the product development process. It is of utmost importance to uphold a high level of quality in the product development process to ensure customer satisfaction. Two critical elements that influence the satisfaction level are the functional and aesthetical requirements regarding the finished product. As an end-user, there is always a general expectation for products to perform well and look great at the same time. Hence, the functional and aesthetical impact of MC is studied in the following sub-sections.

6.2.1 Poor Functional Quality

As mentioned in Section 4.4, the refitting of the body lamp must ensure that the closing of the tailgate must not be affected in any manner. Functionality, in this case, goes hand in hand with aesthetics and is hence an equally important parameter to be studied. The functionality of a component is usually studied over a given period of time to assess its overall performance capability and durability. Hence, the study about functionality requires access to data or a product over a prolonged period. Since this thesis is limited to studying only newly produced cars, the study about how MC affects functional requirements would be left for future research.

6.2.2 Poor Perceived Quality

When analyzed in a perspective connected to geometrical variation, perceived quality as described in Section 2.2.1 is of high relevance. Poor perceived quality leaves behind a negative image in the minds of customers (Wickman & Söderberg, 2010). Gap and flush measures on a car are analyzed in the following text as an effect of MC due to their connection towards geometrical variation. Geometrical variation affects perceived quality in general and has a more significant influence in visually sensitive areas (Wickman & Söderberg, 2010).

Focusing on the split lines on the car, a general concern was expressed within VCC about the gap on the body side in the rear end of certain car models. Even in the Top-Inner-Outer test case mentioned in Section 5.2.4, MC caused due to the change in screw sequence made the outer body lamp shell deviate from the surface of the body to the extent where taking measures was not possible. Even though the probability of this specific screw sequence is low, the impact it leaves behind makes it a critical test case to be considered and studied. Also, the gap along the body side, in that case, was relatively big, as shown in Figure 5.8. The importance shown towards perceived quality can also be understood from the case study on re-fitment of body lamps as mentioned in Section 4.4 where the body lamp was refitted to ensure that the gap requirement was satisfied. In this situation, a possible misconstrain was created by the worker in an attempt to uphold aesthetics. Misconstraining as an error phenomenon observed through geometrical variation makes it essential to address the connection between MC and visually sensitive areas. Focusing on the visually sensitive areas could be a potential way to mask off the variation caused by MC. However, this is a topic for future research that will help reveal the true nature of the interrelationship between visual sensitivity and MC.

6.3 Three Envisioned Forms of Misconstraining

Misconstraining as an error phenomenon has been envisioned to have other forms that revolve around the same problem statement. These forms can be considered to be a type of MC and are closely related with one and another. Branded as the three forms of MC, misguiding, collision of parts, and intended system solution not being satisfied form the sides of a triangular relation as shown in the Figure 6.2. Each of these forms and their associated case studies connected in the following text are in line with their source of origin as mentioned in Section 3.1.2. Thus, all these cases will be interlinked, similar to how the forms would be interlinked with each other. The following subsections will present the envisioned theory behind each of these forms.

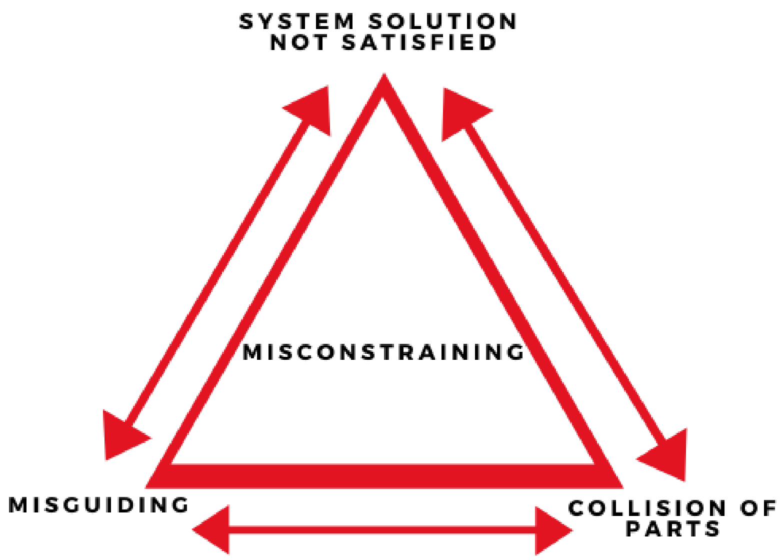

Figure 6.2: Three proposed forms of misconstraining based on the results obtained.

6.3.1 Collision of Parts

Collision of parts can be caused due to a multitude of reasons, but one of its most significant effects is MC. It is easy to spot collisions using virtual tools, but in reality, collision among components cannot be picked up by the naked eye in most cases. When parts collide, they naturally deviate from their ideal position. Depending on the parts' strength or rigidity, the weaker or flexible part undergoes a shift to accommodate the situation. This is a standard case that is widely seen in a lot of applications around our daily life. The collision of parts is said to be considered as a common ordeal connected to MC by many VCC employees, and one of them who was interviewed shared the following statement:

> *"In my opinion, misconstraining is simply a collision of parts that leads to problems in the manual assembly process."*

Just like the rest of the forms of MC, collision of parts is also a form that is mutually interlinked to the other forms and results in one and another as shown in Figure 6.2.

6.3.2 Misguiding

In an assembly consisting of two components, if the parts are misguided somehow, it is natural to expect a certain level of collision between them during the final assembly. For example, in the novel body lamp case, as described before in Section 4.1, the snap-lock was expected to act as a fully steering reference providing guiding in the X, Y, and Z directions. However, it underperformed and did not guide as intended, and hence the entire body lamp setup underwent MC at the end. Furthermore, this caused a collision on the inner screw side as shown in Figure

4.3 which also lead to the intended system solution not being satisfied. Ultimately, misguiding upon its emergence proved to be leading to other forms of MC, as rightly pointed in Figure 6.2.

6.3.3 System Solution Not Satisfied

As shown in Section 3.1.2 it would be possible to assemble the parts in a given way that is not the intended system solution. When this happens, the components involved are likely made to perform in a way that they were not designed for initially. Therefore, it is essential to study this form so that whenever a problem arises concerning geometry, it is not just the system that is blamed but instead how the assembly was carried out is also being investigated. Also, in cases such as the sill moulding case study mentioned in Section 4.3, it would be impossible to notice the error using the naked eye, and the system solution would not have been satisfied in that case.

The three aforementioned forms have been unearthed by analyzing the case studies and the body lamp test cases. It is essential to understand that this envisioning of the concept of MC was necessary altogether due to the novelty of the research topic. So, these forms would surely evolve and transform during future research.

6.4 Checklist to Avoid Misconstraining

The different results obtained have revealed a few significant ways to prevent MC in the product development process. The following recommendations have been developed from a manual assembly perspective and contain information of interest for both the ME and R&D departments at VCC. Apart from the identified checkpoints here, the checklist has to be further developed, and its place in the product development process must be identified moving forward.

1. Is the assembly sequence explicitly mentioned in the PII? (Checking the Description)

    - The presence of information about how the assembly has to take place gives utmost clarity to the manual assembly operator. As seen in the sill moulding case mentioned in Section 4.3, without proper instruction on the assembly sequence, the workers were performing the assembly operation by applying force on the wrong spots, which led to geometric variation.

    - Also, in the case of the body lamp testing mentioned in Section 5.2.4, the change in screw sequence affected the geometrical requirements and made things worse when compared to the standard 3-2-1 screw sequence. Clarity is power; hence it is essential to mention the assembly sequence as explicitly as possible.

2. Is the PII being followed in the assembly line? (Checking the Implementation)

   - This is a typical case of examining or investigating the execution of the PII. As discussed in Section 4.4, the body lamp as per the PII had to be fastened immediately, whereas, in reality, the body lamp was hanged on to the body at the start of the line and fastened at the tail end due to assembly line balancing.

3. Has it been verified if the locators are doing what they are supposed to do?

   - This checkpoint is more for the R&D side of things wherein any basic positioning system decided upon should be checked further for the following key areas and their satisfaction.

     – Tolerances: The minimization of play between the guiding elements and the car body was vital for increasing the system's robustness altogether. As shown in Section 5.2.3, the presence of the tape prevented the rattle between the pin and the slot on the car body, and as a result, an indication of a more stable solution with higher robustness was obtained.

     – Location Scheme: The location scheme checkpoint from an R&D perspective would be to verify the functioning or behavior of the guiding elements through verification prototypes. In the research study mentioned in Section 4.2, the dual snap-lock system solution initially considered a potential solution was later scrapped and replaced by the standard screw solution. Hence, it is necessary to test the functioning of the intended reference system, at least if the proposed solution is a novel concept, using test rigs.

4. Is the feedback loop between ME and R&D clear and verified?

   - The significance of an effective feedback loop was realized through the body lamp case mentioned in Section 4.1. Also, the requirement from the VCC personnel as mentioned in 6.1.5 for the feedback to be more concise, relevant, and backed with proof instead of subjective opinions makes this a key checkpoint.

5. Has there been necessary training or knowledge enhancement provided to the assembly workers in connection to Misconstraining?

   - As mentioned by the authors in Brolin et al. (2017), the cognitive requirements of a worker play a crucial role when it comes to eliminating errors in the assembly process. Hence, it is beneficial to increase the awareness assembly workers have about MC and its causes.

- Provided in the context of a suggestion, more training, and knowledge on the topic would help the workers to react to MC in an agile manner and identify its occurrence just in time for any corrections to be made.

6.5 Reflections and Recommendations for Future Work

This section will explain the scope for future work connected to MC and give a descriptive visualization of the concept evolution as envisioned by the authors. With the future set in sight, implementing these suggestions for future work could enhance the conceptual understanding and development process moving forward.

6.5.1 Concept Immaturity

The awareness and knowledge available about a given concept determine its level of maturity. As mentioned by Mankins (1995) via the Technology Readiness Level (TRL) framework, the development process is extensive. It involves several steps before it can be claimed that full maturity has been attained. MC being a novel area of study, the baby steps of progress achieved through this thesis has set the base for further development. On a contrasting side, it must also be understood that the immature nature of the topic dictates the need to focus on what the test results and case studies are indicating rather than on the magnitude of the results obtained. Probably, with more knowledge gathered over time, the uncertainty about MC will reduce quite similar to how the cone of uncertainty shown in Figure 2.2 describes it, and eventually, the tacit nature of the topic would transform to make more informed decisions. The presence of MC discovered within VCC indicates the importance of the research and that it is likely to find more cases to assist the development of the topic.

6.5.2 Experimental Test Inaccuracy

The results of the test indicate changing the location scheme or change in the screw sequence might influence the geometrical variation, causing a lesser perceived quality, see Figure 5.8. Having this tested for a variety of parts with different location schemes could further strengthen the assumption. Especially since some location schemes are more robust and less coupled than others, as described according to Söderberg, Lindkvist, and Carlson (2006a) presented in Section 2.3.2. The aspect of human error contribution as, covered in 2.4.4, and the results from testing, see Table 5.2, indicate that the difference between humans could potentially affect the geometrical variation and thereby are likely to contribute towards MC.

The tolerance test was given extra attention to strengthening the hypotheses of play between the guiding elements, contributing to the variation. Also, this could be a relatively easy way for VCC to control the variation. The results indicated a decrease in variation between the two cases, see Table 5.8. However, some of the measuring points were not acting as expected. For example, in the phase 2 of the tolerance test, P5-F shows an increase between the 'with tape' and 'without tape' test cases, see Appendix F.4 even though the opposite would be expected. Despite being an anomaly, the results still appear as repeatable. The variation between each measurement suggests that results are acceptable, and a more stable system is achieved using the tape.

To perform all tests on one single setup has its benefits, as mentioned in Section 3.2.5 since previously conducted tests at VCC showed proof of compliant behavior, see Figure 3.6. However, whether the uncontrollable variable of deterioration of the lamp or BIW may affect the result was not considered during testing. Moreover, the number of measures taken might not be enough to use as statistical proof of the areas investigated. Yet, the test in conjunction with the case studies and the literature suggests that tendencies can be observed. To further strengthen the hypotheses and getting proof of the causes, more measurements need to be captured and more parts considered.

Furthermore, the manual hand tightening and relative inexperience in taking accurate measurements that can be categorized as flaws in the measurement technique could have influenced the results. Ultimately, their reliability is to be questioned. Potential inaccuracies could be obtained due to the "high resolution" of the measures, meaning measuring differences in the range of 0.1 [mm] or less. Influencing measurements of this magnitude is relatively easy, especially concerning the gap dependency mentioned in Section 3.2.5. Moreover, unintentional bias might also be present in this type of data collection since the participants are likely to have the preceding measurements and the nominal values as a comparison. Additionally, not conducting all tests on the same day, one after the other, might cause a difference between the tests, even if all tests follow the same procedure. A more automated measurement technique performed by experts could be utilized to address the previously stated concerns.

6.5.3 Inter-relationship Study

Throughout this thesis, the drive has been to map the contributing factors in connection to MC, and indeed the tests and case studies have helped establish proof for the various contributing factors as shown in Figure 6.1. Unfortunately, it has not been possible to study the inter-relationship between the contributing factors due to time constraints. Still, from discussions within VCC, it has been observed that a better understanding of the relationship between these contributing factors could further strengthen the knowledge on the error phenomenon. So, a thorough study about the relationships using an inter-relationship diagram as part of the RCA process might be beneficial moving forward.

6.5.4 Visualization Transformation of Misconstraining

This section of the report discusses the current standpoint on MC and a suggestion about how it could be perceived moving forward. The shift in perception about MC will surely be driven by future research on this topic and its contributing factors.

Current Perception about Misconstraining

Geometrical variation involves both part variation and assembly variation as mentioned by Söderberg, Lindkvist, and Carlson (2006b). As shown in Figure 6.3, MC, part variation, and assembly variation have been studied as interlinked with one and another, and MC has always been considered as a subset within geometrical variation in this thesis. The same is reflected in how the problem has been defined in Section 1.3 and how assembly variation in measures as mentioned in Section 5.2 was observed in all the test cases conducted to try and find the causes connected to MC. Therefore in this current perspective, geometric variation which includes both assembly and part variation is how MC is being addressed as shown in Figure 6.3.

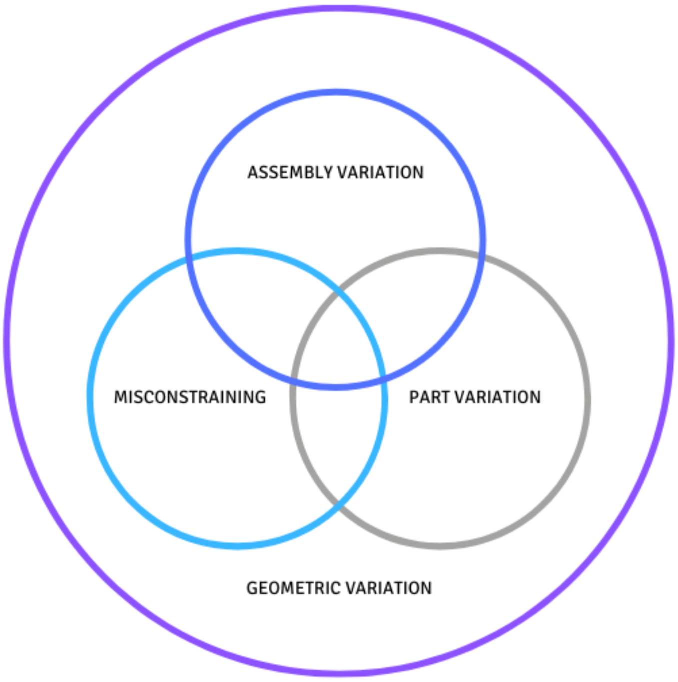

Figure 6.3: Venn diagram presenting the current thought about Misconstraining.

It is essential to understand that all MC is accounted for as geometric variation. Still, not all geometric variation is MC, and the process of finding what is included in MC and what is not will be left for future work.

Envisioned Idea for Future Work

A future look into the concept was developed to assist further development. Figure 6.4 presents the thought process that MC must be treated partially independent of geometric variation to a given extent where there would still be an intersection zone. This intersection zone marked as to be decided or 'TBD' is where geometrical variation can be solely categorized as MC and would make it possible to know what is to be included and what is left out. Future work into this topic will provide a much better understanding of MC, and extensive mapping of the causes would greatly benefit this Venn diagram ideology. Through this approach, MC gets treated with a high level of autonomy, and its effects can be studied with a broader perspective.

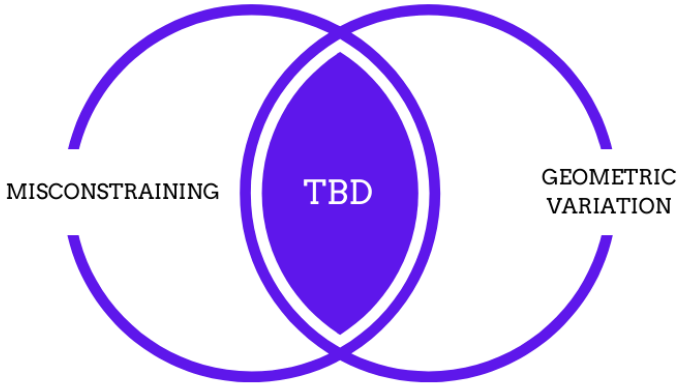

Figure 6.4: Venn diagram presenting the expected outcome with regards to Misconstraining in the future.

6.5.5 Misconstraining in Conjunction with Compliancy

It has been observed that the car body shows signs of compliant behavior in the region where the body lamp is mounted, and a primary reason behind this is the thin layer of sheet metal in this section. A glimpse of this is shown in Figure 3.6. This is the aftermath of torquing a V60 body lamp onto the painted body, and as seen in the image, the deformation on the body in the region around the screws reflects the non-rigid nature.

Any deformation might lead to geometric variation if the deformation had not been accounted for in the earlier stages of the product development process itself. When the body gets deformed, the relative positioning of the components gets affected. This might have an immediate effect on the aesthetic aspects of the car, like perceived quality, or might influence the functionality of the component moving forward. MC, as defined in Section 1.3, affects the aesthetics or functionality of the component involved. Hence it is critical to further study accounting for compliancy quite early in the product development process to prevent MC from occurring altogether. The following statement from an experienced geometry engineer summarizes the viewpoint regarding compliant behavior and its relation to MC.

> *"Compliant behavior is necessary to be accounted for, especially in these regions where the sheet metal is thin. However, it is skipped due to the difficulty involved in the process and the change in results it provides for the time and effort put into it."*

7 Conclusion

The concept of misconstraining has been a challenging yet paramount area to study concerning the manual assembly process. Reflecting on the study's purpose, MC had long been an implicit area that had not been previously researched in VCC. With this thesis, the novelty barrier has been broken, and credible information connected to MC has been collected. The various experimental tests and the case studies carried out in the thesis have helped identify potential contributors to MC, such as human error, assembly sequence issues, tolerance play between guiding elements, and feedback loop issues. Also, insights into the effects of MC and their forms have been developed to assist future research. Summarizing all the knowledge acquired so far, this chapter will elucidate how the RQ's have been answered by the work performed during the thesis.

7.1 Objective Fulfillment

1. What is misconstraining, and what are its prominent causes in the manual assembly process?

    - Misconstraining as a theoretical concept is defined as an error phenomenon that could be caused by inaccuracies in the assembly process or when parts being assembled are out of specification. It is important to understand that MC, assembly variation, and part variation partially intersect with one and another as shown in 6.3. Hence neither part variation nor assembly variation is wholly inclusive in MC. As mentioned in Section 1.3, this study has been performed on a GA perspective with geometrical variation as the means to identify the presence of MC. The fishbone diagram shown in Figure 6.1 presents the complete picture of the causes identified as primary contributors to MC so far. The reasoning behind the same has been elucidated in detail under Section 6.1.

2. What are the effects of misconstraining?

    - The cases dealt with in this thesis have on numerous instances highlighted the impact MC has on aesthetics. The same has been discussed in Section 6.2 explaining how MC becomes a predicament in connection to perceived quality. Considering the case studies and test results performed in the thesis, it is safe to say that MC influences the aesthetics or perceived quality of the car.

3. How does misconstraining influence the geometrical requirements in the product development process moving forward?

    - The case studies presented in Sections 4.3 and 4.2 serve as knowledge about the probable impact of having an incomplete PII as well as a failed dual snap lock positioning setup. This information will help make informed decisions regarding the positioning system and the locating scheme moving forward. Also, the tolerance tests presented in Section 5.2.3 studied concerning MC have helped discover the importance of eliminating the play between the guiding elements. Misconstraining and the studies performed in connection to the phenomenon will influence the tolerance choices and locating schemes moving forward in the product development process.

4. What methodology/framework can be developed to minimize the risk of misconstraining?

    - The checklist comprising of the list of recommendations as presented in Section 6.4 elucidates the preliminary framework that could help curb MC. With further studies conducted in connection to MC, the knowledge gained will help expand the checklist, fine-tune the existing recommendations and find a suitable spot for the checklist to be placed within the product development process at VCC.

To conclude, misconstraining perceived as an error phenomenon is challenging to study and presents its own set of limitations regarding what is categorized to be misconstraining and what is not. However, it is a microscopic phenomenon with a massive potential for future research, especially in the manual assembly process. The fuzzy front end of developing this theoretical concept has helped reduce the tacitness or implicit nature of the topic. However, it still might have some grey areas that need further attention moving forward. Furthermore, maintaining screw sequence is vital to preventing MC, and reducing the play between guiding elements helps reduce geometrical variation and produce a more robust system.

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Appendices

A The 16 HC criteria

Criterion 1, interpretation:
If in case there are multiple ways in which the assembly of the parts or the overall task could be performed correctly, then it is classified as HC. Otherwise, the classification given is a LC.

Criterion 2, interpretation:
The Individual Details (ID) take into account the number of parts that must be mounted or fastened. All the preassembled components or parts like the reference pins are to be neglected. On the other hand, part Operations (PO) refers to the total number of assembly operations that consume time measured in TMU in the manual assembly process. The sum of ID and PO, if greater than seven, can be classified as HC. Anything in the range of 0-6 can be classified as LC.

Criterion 3, interpretation:
The evaluation of this criterion is directly related to the combination of different operations performed at the same time. As quoted by the developer, "The median assembly time of the longest part operation of many operations was used as limit value (e.g., 105 TMU = approx. 4 sec. in a recent car assembly study)."

Criterion 4, interpretation:
If the following current parameters are not fulfilled for every part operation or component, the task should be assessed as HC, or else it can be classified as LC.

- Guiding/controlling
- Reference systems
- Reference pins
- Fixtures
- Clips/screws
- Latches
- Controlling spline
- Rotation stop
- Snaps, hooks
- T-studs (integrated reference system)
- Tracks or cuts

Criterion 5, interpretation:
Having insufficient access for hands or the hands and tool along with the body part is termed as poor accessibility and is classified as HC.

Criterion 6, interpretation:
If the area where the part is mounted or assembled is away from the field of view of the operator when looking at the car from the outside, then the task is to be classified as HC. If in case visibility exists, then the task is to be classified as LC.

Criterion 7, interpretation:
A standard ergonomics checklist as regulated by the Swedish law and European directives must be employed for the assessment of this criterion. Based on the evaluation results, the tasks will be classified as HC or LC.

Criterion 8, interpretation:
The task under this criterion is classified as HC if there is a requirement for training exercises in addition to the introductory session or if the station is not suitable for the newly employed right after the introduction.

Criterion 9, interpretation:
The task is classified as HC when the assembly needs to be done in a specific order to ensure that it is done in the right manner. If the order does not matter, then the classification can be LC.

Criterion 10, interpretation:
The task is classified as HC if subjective assessment like touch and visual inspection is to be done and is mentioned as a part of the description to secure good quality. Else it can be termed as LC .

Criterion 11, interpretation:
If there are high demands on fine motor skills of the operator or high precision demanding work like fitting a detail within millimeters or assembly from a long distance to the detail, then the operation should be considered as HC.

Criterion 12, interpretation:
If frequent adjustment of the equipment at the workstations is needed for preventing errors from occurring, then the task that is performed at that station is termed as HC.

Criterion 13, interpretation:
If there is a lot of variation in the surrounding components or if the part to be assembled is dependent on the surrounding component, then this is a typical example of the geometric environment having a lot of variation. Then the job is termed as HC. To assess the degree of complexity, the following should be done:

- Check the tolerances.
- Are the products within the tolerance limits?
- Is there a risk the parts cannot be assembled due to the tolerances?
- Tolerances close to or outside the limits?

Criterion 14, interpretation:
If there a risk of errors occurring or poor quality output if the work instructions are not accurately followed, then this criterion should be assessed as HC. Questions to be used for assessment are:

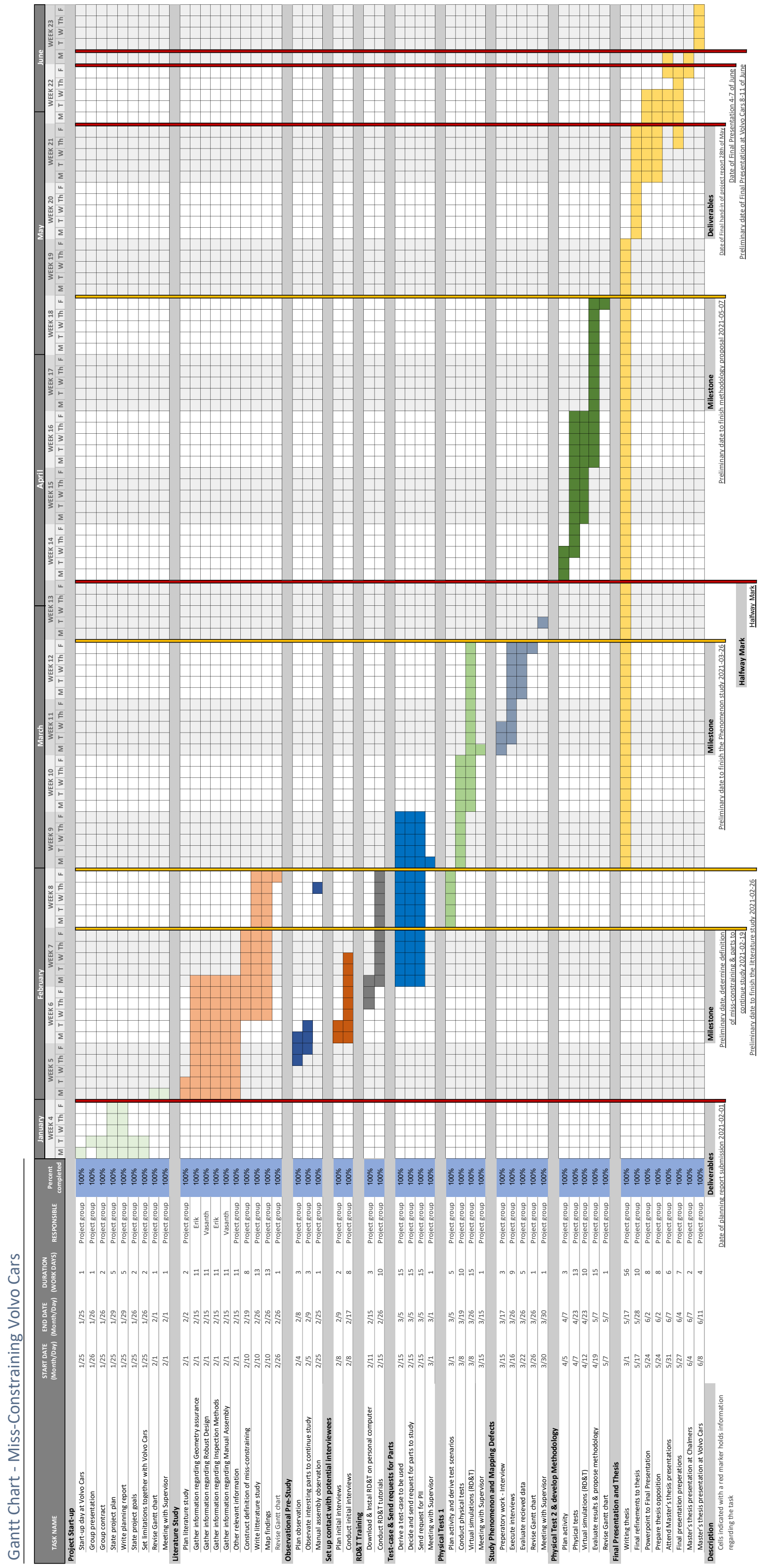
- In what order are components going to be assembled.
- How is the assembly going to be done, i.e., with what tools/components?

Criterion 15, interpretation:
The following examples of material are considered as soft and flexible and are often challenging to be placed in a geometrically correct manner.

- Rubber strips and rubber plugs.
- Cables and wires
- Carpets
- Some panels and covering material
- Safety Belts
- Tubes and hoses
- Tottering material/parts/components

Criterion 16, interpretation:
If feedback upon assembly either in the form of a sound or feel is obtained, then the operation or job is classified as LC. Or else the task is termed as HC since verification of the fitment is difficult.

B Gantt Chart



C Interviewees

Interviewees from the academic side. Conducted to get a view over previously conducted research and was a part of the initial interviews.

Nr.	Institution	Expertise
1	Chalmers	RD&T
2	Chalmers	AMIGO
3	Chalmers	16 HC

Interviewees from VCC. Conducted to gain knowledge about misconstraining and related issues. Note that the purpose column is indicated with Initial (I) or Case Study (CS) depending on the type of interview.

Nr.	Purpose	Department	Role
1	I	Geometry Assurance Program	Geometry Leader ME
2	I	Geometry Assurance VCMT	Systems Assurance Engineer (running production)
3	I	Geometry Assurance Program	Geometry Assurance Engineer
4	I	ME Geometry	Geometry Assurance Engineer
5	I	ME	Program Commodity Leader
6	CS	Robust Design & Tolerancing	Senior Robust Design Engineer
7	CS	Robust Design & Tolerancing	Robust Design Engineer
8	CS	Robust Design & Tolerancing	Robust Design Engineer (Consultant)

D Interview Guide Academia

This standard interview guide was used during the initial interview with persons connected with the academia. The guide was modified to be more aligned to the interviewees profession and expertise.

1. Tell us about your background
2. What are your thoughts on misconstraining or tjuvstyrning?
3. Can you tell us about the AMIGO project and work related to it?
4. What is the drive behind the project?
5. Can you tell us about real time studies conducted at Volvo cars in connection to misconstraining?
6. What drove you to look into the 16 HC criteria?
7. Why do you feel that the 16 High Complexity (HC) critera are key factors to be considered?
8. Has the 16 HC criteria developed in RD&T been implemented by the industry?
9. Who/ which department do you foresee utilizing the HC criteria in their role?
10. What are your thoughts on taking a research-based route for a project that revolves around practical errors in the manual assembly process?
11. What do you believe the main reason/ contributing factor to miss-constraining is?
12. Is there any current research being carried out about assembly errors and their causes?
13. Do you think it is worth to look into misconstraining from an organization perspective?
14. Do you have other peoples in mind that you think would be interesting for us to have a similar conversation with?

E Interview Guide Volvo Car Corporation

This standard interview guide was used during the initial interview with persons within VCC. The guide was later modified to be aligned to the interviewees profession and expertise.

1. Please tell us about your background.
2. What previous occupations within Volvo Cars have you had?
3. Can you tell us about your current job, how is a typical work day?
4. Where in the assembly line do you think most errors occur?
5. Any part that you know of that is extra problematic both in terms of design and/ or assembly?
6. What do you think these errors originates from?
7. What is your perception about misconstraining/ parts being misconstrained?
8. How big of a problem do you think parts being misconstrained are?
9. When do you think miss-constraining becomes a problem?
10. What do you think is the main reason why parts are being misconstrained?
11. What are you/ your coworkers doing today to prevent misconstraining or similar errors from occurring?
12. Is there any cooperation's between departments in order to prevent these kinds of errors?
13. Who determine the assembly sequence?
14. Who follows up that the assembly sequence is being followed?
15. Do you have anyone in mind that could be interesting for us to have similar conversation with?

F Test Results

F.1 Capability Test

Projekt **Master's Thesis**

Duglighetsstudier av mätutrustning

Date

PKI Nr. | Artikelbenämning | Masternamn | Operatör A **Erik Arvidsson** | Operatör B **Vasanth Kumar**

Detalj-Löpnr.	Mätpunkt P1-F (Verktygsnr.)		
	Op A	Op B	RA-B
1	0,61	0,65	0,04
2	0,69	0,67	0,02
3	0,68	0,69	0,01
4	0,62	0,68	0,06
5	0,67	0,68	0,01
Variation R	$\frac{\sum R}{5}$	$\frac{0,14}{5}$	0,028
Tolerans-vidd, T	T=	± 1	2
Duglighet C %	$\frac{R*4,33*100}{T}$		6,1

Detalj-Löpnr.	Mätpunkt P2-F (Verktygsnr.)		
	Op A	Op B	RA-B
1	1,21	1,29	0,08
2	1,28	1,42	0,14
3	1,27	1,44	0,17
4	1,21	1,41	0,20
5	1,23	1,42	0,19
Variation R	$\frac{\sum R}{5}$	$\frac{0,78}{5}$	0,156
Tolerans-vidd, T	T=	± 1	2
Duglighet C %	$\frac{R*4,33*100}{T}$		33,8

Detalj-Löpnr.	Mätpunkt P3-F (Verktygsnr.)		
	Op A	Op B	RA-B
1	2,34	2,44	0,10
2	2,36	2,54	0,18
3	2,39	2,45	0,06
4	2,42	2,51	0,09
5	2,41	2,71	0,30
Variation R	$\frac{\sum R}{5}$	$\frac{0,73}{5}$	0,146
Tolerans-vidd, T	T=	± 1	2
Duglighet C %	$\frac{R*4,33*100}{T}$		31,6

Detalj-Löpnr.	Mätpunkt P4-F (Verktygsnr.)		
	Op A	Op B	RA-B
1	1,66	1,66	0,00
2	1,59	1,74	0,15
3	1,67	1,60	0,07
4	1,68	1,68	0,00
5	1,66	1,74	0,08
Variation R	$\frac{\sum R}{5}$	$\frac{0,30}{5}$	0,060
Tolerans-vidd, T	T=	± 1	2
Duglighet C %	$\frac{R*4,33*100}{T}$		13,0

Detalj-Löpnr.	Mätpunkt P5-F (Verktygsnr.)		
	Op A	Op B	RA-B
1	1,11	0,71	0,40
2	1,08	0,77	0,31
3	1,10	0,85	0,25
4	1,10	1,03	0,07
5	1,09	0,81	0,28
Variation R	$\frac{\sum R}{5}$	$\frac{1,31}{5}$	0,262
Tolerans-vidd, T	T=	± 1	2
Duglighet C %	$\frac{R*4,33*100}{T}$		56,7

Detalj-Löpnr.	Mätpunkt P6-F (Verktygsnr.)		
	Op A	Op B	RA-B
1	0,85	0,79	0,06
2	0,86	0,90	0,04
3	0,83	0,87	0,04
4	0,82	0,89	0,07
5	0,88	0,86	0,02
Variation R	$\frac{\sum R}{5}$	$\frac{0,23}{5}$	0,046
Tolerans-vidd, T	T=	± 1	2
Duglighet C %	$\frac{R*4,33*100}{T}$		10,0

F.2 Human Error Contribution Test

Operator	Assy. nr.	P1 - Flush	P1 - Gap	P2 - Flush	P2 - Gap	P3 - Flush	P3 - Gap	P4 - Flush	P4- Gap	P5 - Flush	P5 - Gap	P6 - Flush	P6 - Gap
		Final Demand Points →											
A	1	-0,77	2,00	-1,28	2,90	-2,71	2,90	-1,82	1,80	-1,19	1,00	-0,96	1,40
	2	-0,88	2,10	-1,50	2,80	-2,70	2,80	-1,88	1,90	-1,32	1,10	-0,85	1,50
	3	-0,80	2,00	-1,53	2,60	-2,36	2,30	-1,64	1,50	-1,28	1,10	-0,85	1,40
	4	-0,90	2,00	-1,60	2,40	-2,40	2,20	-1,63	1,50	-1,32	1,20	-0,87	1,30
	5	-1,00	2,10	-1,49	2,70	-2,75	2,80	-1,89	1,60	-1,36	1,00	-0,84	1,40
	MIN	-1,00	2,00	-1,60	2,40	-2,75	2,20	-1,89	1,50	-1,36	1,00	-0,96	1,30
	MAX	-0,77	2,10	-1,28	2,90	-2,36	2,90	-1,63	1,90	-1,19	1,20	-0,84	1,50
	Skillnad	**-0,23**	**-0,10**	**-0,32**	**-0,50**	**-0,39**	**-0,70**	**-0,26**	**-0,40**	**-0,17**	**-0,20**	**-0,12**	**-0,20**

Operator	Assy. nr.	P1 - Flush	P1 - Gap	P2 - Flush	P2 - Gap	P3 - Flush	P3 - Gap	P4 - Flush	P4- Gap	P5 - Flush	P5 - Gap	P6 - Flush	P6 - Gap
		Final Demand Points →											
B	1	-0,90	1,90	-1,60	2,30	-2,36	2,10	-1,60	1,40	-1,32	1,10	-0,89	1,30
	2	-0,99	1,90	-1,68	2,30	-2,44	2,20	-1,69	1,50	-1,32	1,10	-0,85	1,40
	3	-0,97	1,90	-1,67	2,20	-2,29	1,90	-1,58	1,30	-1,31	1,20	-0,86	1,30
	4	-0,99	1,90	-1,60	2,10	-2,30	2,00	-1,56	1,30	-1,34	1,00	-0,85	1,30
	5	-0,99	1,90	-1,62	2,20	-2,40	2,10	-1,63	1,40	-1,33	1,10	-0,88	1,30
	MIN	-0,99	1,90	-1,68	2,10	-2,44	1,90	-1,69	1,30	-1,34	1,00	-0,89	1,30
	MAX	-0,90	1,90	-1,60	2,30	-2,29	2,20	-1,56	1,50	-1,31	1,20	-0,85	1,40
	Skillnad	**-0,09**	**0,00**	**-0,08**	**-0,20**	**-0,15**	**-0,30**	**-0,13**	**-0,20**	**-0,03**	**-0,20**	**-0,04**	**-0,10**

		P1 - Flush	P1 - Gap	P2 - Flush	P2 - Gap	P3 - Flush	P3 - Gap	P4 - Flush	P4- Gap	P5 - Flush	P5 - Gap	P6 - Flush	P6 - Gap
A&B	Mean A	-0,870	2,040	-1,480	2,680	-2,584	2,600	-1,772	1,660	-1,294	1,080	-0,874	1,400
	Mean B	-0,968	1,900	-1,634	2,220	-2,358	2,060	-1,612	1,380	-1,324	1,100	-0,866	1,320
	Difference	**0,098**	**0,140**	**0,154**	**0,460**	**0,226**	**0,540**	**0,160**	**0,280**	**0,030**	**0,020**	**0,008**	**0,080**

F.3 Tolerance Test

Case	Assy. nr.	Final Demand Points →					
		P1 - Flush	P2 - Flush	P3 - Flush	P4 - Flush	P5 - Flush	P6 - Flush
Pushing in (PI)	1	-0,66	-1,25	-2,45	-1,87	-1,14	-0,77
	2	-0,76	-1,36	-2,59	-1,86	-1,17	-0,75
	3	-0,75	-1,38	-2,48	-1,83	-1,15	-0,75
	4	-0,77	-1,33	-2,60	-1,88	-1,19	-0,77
	5	-0,69	-1,28	-2,59	-1,89	-1,16	-0,71
	MIN	-0,77	-1,38	-2,60	-1,89	-1,19	-0,77
	MAX	-0,66	-1,25	-2,45	-1,83	-1,14	-0,71
	Skillnad	**-0,11**	**-0,13**	**-0,15**	**-0,06**	**-0,05**	**-0,06**

Case	Assy. nr.	Final Demand Points →					
		P1 - Flush	P2 - Flush	P3 - Flush	P4 - Flush	P5 - Flush	P6 - Flush
TAPE Pushing in (PI)	1	-0,88	-1,58	-2,41	-1,59	-1,28	-0,84
	2	-0,99	-1,72	-2,43	-1,60	-1,35	-0,78
	3	-0,96	-1,62	-2,53	-1,66	-1,33	-0,77
	4	-0,95	-1,66	-2,35	-1,58	-1,28	-0,80
	5	-0,92	-1,62	-2,48	-1,63	-1,29	-0,77
	MIN	-0,99	-1,72	-2,53	-1,66	-1,35	-0,84
	MAX	-0,88	-1,58	-2,35	-1,58	-1,28	-0,77
	Skillnad	**-0,11**	**-0,14**	**-0,18**	**-0,08**	**-0,07**	**-0,07**

Case	Assy. nr.	Final Demand Points →					
		P1 - Flush	P2 - Flush	P3 - Flush	P4 - Flush	P5 - Flush	P6 - Flush
Pushing Out (PO)	1	-0,72	-1,24	-2,43	-1,64	-0,91	-0,55
	2	-0,79	-1,27	-2,47	-1,67	-0,93	-0,56
	3	-0,77	-1,26	-2,42	-1,63	-0,92	-0,48
	4	-0,81	-1,33	-2,33	-1,53	-0,92	-0,57
	5	-0,79	-1,34	-2,10	-1,41	-0,87	-0,57
	MIN	-0,81	-1,34	-2,47	-1,67	-0,93	-0,57
	MAX	-0,72	-1,24	-2,10	-1,41	-0,87	-0,48
	Skillnad	**-0,09**	**-0,10**	**-0,37**	**-0,26**	**-0,06**	**-0,09**

Case	Assy. nr.	Final Demand Points →					
		P1 - Flush	P2 - Flush	P3 - Flush	P4 - Flush	P5 - Flush	P6 - Flush
TAPE Pushing Out (Po)	1	-1,01	-1,62	-2,21	-1,38	-1,11	-0,69
	2	-0,99	-1,61	-2,42	-1,60	-1,15	-0,73
	3	-1,03	-1,63	-2,40	-1,55	-1,16	-0,74
	4	-0,97	-1,56	-2,56	-1,67	-1,12	-0,74
	5	-1,00	-1,66	-2,27	-1,43	-1,15	-0,71
	MIN	-1,03	-1,66	-2,56	-1,67	-1,16	-0,74
	MAX	-0,97	-1,56	-2,21	-1,38	-1,11	-0,69
	Skillnad	**-0,06**	**-0,10**	**-0,35**	**-0,29**	**-0,05**	**-0,05**

PI & PO	Mean PI	-0,726	-1,320	-2,542	-1,866	-1,162	-0,750
	Mean PA	-0,776	-1,288	-2,350	-1,576	-0,910	-0,546
	Difference	**0,050**	**0,032**	**0,192**	**0,290**	**0,252**	**0,204**

PI & PO	Mean PI	-0,940	-1,640	-2,440	-1,612	-1,306	-0,792
	Mean PA	-1,000	-1,616	-2,372	-1,526	-1,138	-0,722
	Difference	**0,060**	**0,024**	**0,068**	**0,086**	**0,168**	**0,070**

F.4 Phase Two Tolerance Test

Case	Assy. nr.	Final Demand Points →					
		P1 - Flush	P2 - Flush	P3 - Flush	P4 - Flush	P5 - Flush	P6 - Flush
Pushing in (PI)	1	-0,62	-1,08	-2,05	-1,18	-0,54	-0,88
	2	-0,58	-1,08	-2,04	-1,34	-0,67	-0,99
	3	-0,55	-0,95	-2,06	-1,20	-0,60	-0,93
	4	-0,63	-1,01	-2,02	-1,18	-0,62	-0,95
	5	-0,66	-1,10	-1,97	-1,12	-0,54	-0,87
	6	-0,74	-1,18	-1,92	-1,15	-0,65	-0,88
	7	-0,67	-1,07	-2,02	-1,22	-0,64	-0,98
	8	-0,62	-0,99	-2,00	-1,23	-0,61	-0,86
	9	-0,64	-1,00	-1,93	-1,19	-0,59	-0,89
	10	-0,64	-1,03	-2,06	-1,19	-0,60	-0,98
	MIN	-0,74	-1,18	-2,06	-1,34	-0,67	-0,99
	MAX	-0,55	-0,95	-1,92	-1,12	-0,54	-0,86
	Skillnad	-0,19	-0,23	-0,14	-0,22	-0,13	-0,13

Case	Assy. nr.	Final Demand Points →					
		P1 - Flush	P2 - Flush	P3 - Flush	P4 - Flush	P5 - Flush	P6 - Flush
TAPE Pushing in (PI)	1	-0,55	-1,06	-2,10	-1,36	-0,71	-0,84
	2	-0,61	-1,11	-2,01	-1,29	-0,70	-0,80
	3	-0,51	-0,95	-2,09	-1,33	-0,67	-0,87
	4	-0,53	-0,95	-2,05	-1,39	-0,69	-0,84
	5	-0,55	-0,96	-2,16	-1,35	-0,73	-0,85
	6	-0,57	-0,97	-2,09	-1,37	-0,73	-0,80
	7	-0,60	-1,12	-2,05	-1,27	-0,72	-0,80
	8	-0,60	-1,11	-2,05	-1,28	-0,78	-0,84
	9	-0,59	-1,01	-2,09	-1,40	-0,73	-0,84
	10	-0,59	-1,03	-2,13	-1,44	-0,73	-0,83
	MIN	-0,61	-1,12	-2,16	-1,44	-0,78	-0,87
	MAX	-0,51	-0,95	-2,01	-1,27	-0,67	-0,80
	Skillnad	-0,10	-0,17	-0,15	-0,17	-0,11	-0,07

Case	Assy. nr.	Final Demand Points →					
		P1 - Flush	P2 - Flush	P3 - Flush	P4 - Flush	P5 - Flush	P6 - Flush
Pushing Out (PO)	1	-0,58	-0,94	-1,93	-1,01	-0,36	-0,52
	2	-0,53	-0,82	-1,78	-0,93	-0,26	-0,55
	3	-0,54	-0,84	-1,65	-0,93	-0,32	-0,65
	4	-0,62	-0,97	-1,66	-0,91	-0,35	-0,64
	5	-0,54	-0,85	-1,87	-1,04	-0,36	-0,65
	6	-0,54	-0,89	-1,85	-1,02	-0,33	-0,66
	7	-0,58	-0,97	-1,82	-1,12	-0,36	-0,62
	8	-0,55	-0,87	-1,87	-1,10	-0,39	-0,59
	9	-0,63	-0,93	-1,80	-1,12	-0,35	-0,65
	10	-0,54	-0,93	-1,90	-1,14	-0,38	-0,65
	MIN	-0,63	-0,97	-1,93	-1,14	-0,39	-0,66
	MAX	-0,53	-0,82	-1,65	-0,91	-0,26	-0,52
	Skillnad	-0,10	-0,15	-0,28	-0,23	-0,13	-0,14

Case	Assy. nr.	Final Demand Points →					
		P1 - Flush	P2 - Flush	P3 - Flush	P4 - Flush	P5 - Flush	P6 - Flush
TAPE Pushing Out (PO)	1	-0,58	-1,01	-1,95	-1,18	-0,55	-0,69
	2	-0,55	-0,93	-1,99	-1,17	-0,57	-0,69
	3	-0,53	-1,01	-2,02	-1,20	-0,52	-0,67
	4	-0,52	-0,95	-2,03	-1,17	-0,51	-0,66
	5	-0,54	-0,97	-2,06	-1,23	-0,56	-0,65
	6	-0,53	-0,97	-2,03	-1,17	-0,55	-0,69
	7	-0,52	-0,95	-2,01	-1,18	-0,57	-0,67
	8	-0,54	-0,97	-2,04	-1,23	-0,56	-0,68
	9	-0,51	-0,98	-1,97	-1,28	-0,52	-0,68
	10	-0,54	-0,97	-2,05	-1,28	-0,53	-0,68
	MIN	-0,58	-1,01	-2,06	-1,28	-0,57	-0,69
	MAX	-0,51	-0,93	-1,95	-1,17	-0,51	-0,65
	Skillnad	-0,07	-0,08	-0,11	-0,11	-0,06	-0,04

PI & PO	Mean PI	-0,635	-1,049	-2,007	-1,200	-0,606	-0,921
	Mean PA	-0,565	-0,901	-1,813	-1,032	-0,346	-0,618
	Difference	0,070	0,148	0,194	0,168	0,260	0,303

PI & PO	Mean PI	-0,570	-1,027	-2,082	-1,348	-0,719	-0,831
	Mean PA	-0,536	-0,971	-2,015	-1,209	-0,544	-0,676
	Difference	0,034	0,056	0,067	0,139	0,175	0,155

F.5 Screw Sequence Test

Screw order	Assy. nr.	Final Demand Points →											
		P1 - Flush	P1 - Gap	P2 - Flush	P2 - Gap	P3 - Flush	P3 - Gap	P4 - Flush	P4- Gap	P5 - Flush	P5 - Gap	P6 - Flush	P6 - Gap
OTI	1	-0,90	1,90	-1,60	2,30	-2,36	2,10	-1,60	1,40	-1,32	1,10	-0,89	1,30
	2	-0,99	1,90	-1,68	2,30	-2,44	2,20	-1,69	1,50	-1,32	1,10	-0,85	1,40
	3	-0,97	1,90	-1,67	2,20	-2,29	1,90	-1,58	1,30	-1,31	1,20	-0,86	1,30
	4	-0,99	1,90	-1,60	2,10	-2,30	2,00	-1,56	1,30	-1,34	1,00	-0,85	1,30
	5	-0,99	1,90	-1,62	2,20	-2,40	2,10	-1,63	1,40	-1,33	1,10	-0,88	1,30
	MIN	-0,99	1,90	-1,68	2,10	-2,44	1,90	-1,69	1,30	-1,34	1,00	-0,89	1,30
	MAX	-0,90	1,90	-1,60	2,30	-2,29	2,20	-1,56	1,50	-1,31	1,20	-0,85	1,40
	Skillnad	**-0,09**	**0,00**	**-0,08**	**-0,20**	**-0,15**	**-0,30**	**-0,13**	**-0,20**	**-0,03**	**-0,20**	**-0,04**	**-0,10**

Screw order	Assy. nr.	Final Demand Points →											
		P1 - Flush	P1 - Gap	P2 - Flush	P2 - Gap	P3 - Flush	P3 - Gap	P4 - Flush	P4- Gap	P5 - Flush	P5 - Gap	P6 - Flush	P6 - Gap
ITO	1	0,06	2,20	-0,55	3,00	-2,21	3,10	-1,37	2,00	-0,72	1,10	-0,76	1,60
	2	0,25	2,30	-0,51	3,10	-2,60	3,20	-1,33	2,00	-0,67	1,00	-0,59	1,50
	3	0,40	2,20	-0,44	3,00	-2,06	3,20	-1,32	2,00	-0,66	1,10	-0,47	1,50
	4	0,14	2,20	-0,82	3,20	-2,13	3,00	-1,36	1,80	-0,77	1,20	-0,42	1,50
	5	0,13	2,30	-0,69	2,90	-2,03	2,80	-1,27	1,80	-0,74	1,10	-0,53	1,50
	MIN	0,06	2,20	-0,82	2,90	-2,60	2,80	-1,37	1,80	-0,77	1,00	-0,76	1,50
	MAX	0,40	2,30	-0,44	3,20	-2,03	3,20	-1,27	2,00	-0,66	1,20	-0,42	1,60
	Skillnad	**-0,34**	**-0,10**	**-0,38**	**-0,30**	**-0,57**	**-0,40**	**-0,10**	**-0,20**	**-0,11**	**-0,20**	**-0,34**	**-0,10**

OTI & ITO	Mean OTI	-0,968	1,900	-1,634	2,220	-2,358	2,060	-1,612	1,380	-1,324	1,100	-0,866	1,320
	Mean ITO	0,196	2,240	-0,602	3,040	-2,206	3,060	-1,330	1,920	-0,712	1,100	-0,554	1,520
	Difference	**1,164**	**0,340**	**1,032**	**0,820**	**0,152**	**1,000**	**0,282**	**0,540**	**0,612**	**0,000**	**0,312**	**0,200**

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