Analyzing manual assembly complexity using a combination of RD&T and IPS IMMA

Validation, proposal of improvements and suggested implementation of the software in the work process at CEVT

Master's thesis in Production Engineering

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Abstract

In the industry, especially the automotive industry, manual assembly is still a significant part of the manufacturing process. In previous research, it has been established that higher manual assembly complexity increases the risk of operator mistakes and thereby may lead to poorer geometrical quality. Therefore, a new software combining the geometry assurance program RD&T and the ergonomics evaluation program IPS IMMA was developed. The program was created to gain information regarding manual assembly complexity earlier in the product development process before changes become more costly.

In this master thesis, the research questions considered whether a validation could be performed on the combined program for a case study, finding potential improvements for the program, and how it could be implemented in the work process at CEVT. The project was divided into three phases, preparation, implementation, and analysis. In the preparation phase, the project was defined and a literature study was performed. In the implementation phase, the validation of the program and interviews were conducted and in the analysis phase, the result from the implementation phase was analyzed.

The validation for the program was a comparison between a manual assessment and the result of the simulation program. The result of the validation was highly impacted by the tuning of the criteria and the limitation of only performing one assembly movement. The conclusion was that the program is not yet ready to be validated. From the validation and the interviews, several improvements were suggested for the program. The interviews provided potential functions based on needs and improvements regarding use in work. The validation contributed to more specific improvements, based on observations from the performed validation. For the implementation in the work processes, it was proposed the analysis of the combined program should be performed by either the geometry department or a support function in the design departments. The general responsibility for the analysis would be shared with the manufacturing feasibility department.

Keywords: manual assembly, manual assembly complexity, complexity criteria, geometry assurance, manufacturing, validation

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Emelie Johansson and Isabella Sten Gothenburg, June 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AMIGO	Analys med manikin för bättre geometrisk kvalitet vid manuell montering, (Analysis with a manikin for better geometric quality during manual assembly, [Authors' translation])
CAT	Computer Aided Tolerancing
CEVT	China Euro Vehicle Technology
CMM	Coordinate Measuring Machine
DHM	Digital Human Modeling
DMAIC	Define Measure Analyze Improve Control
DOF	Degrees of Freedom
DM	Design Matrix
DP	Design Parameter
FR	Functional Requirement
GD&T	Geometric Design and Tolerancing
HC	High Complexity
IMMA	Intelligently Moving Manikin
IPS	Industrial Path Solutions
LC	Low Complexity
PQ	Perceived Quality
RCA	Root Cause Analysis
RD&T	Robust Design & Tolerancing
REBA	Rapid Entire Body Assessment
RMS	Root Mean Square
RULA	Rapid Upper Limb Assessment
TMU	Time Measure Unit
VIM	Vehicle Integration Meeting

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1
Introduction

In this chapter, the introduction of this master thesis is presented. It gives a background to the problem, aim, research question, and limitations. The project is conducted at the company CEVT (China Euro Vehicle Technology), to validate a simulation tool combining Robust Design and Tolerancing (RD&T) and Industrial Path Solutions (IPS) using the module Intelligently Moving Manikin (IMMA).

1.1 Background

CEVT is an innovation and technology company located in Sweden, near some of the greatest car manufacturers (CEVT, 2021b). Their focus is on research within mobility, including modular development, software development, virtual engineering, and innovation (CEVT, 2021a). The company is a subsidiary of Zhejiang Geely Holding Group, which is a global automotive group, that also owns other well-known car brands, such as Volvo Cars (CEVT, 2021b). This project is ordered by the Body and Geometry department at CEVT, which is working with geometry assurance in product development. Geometry assurance can be explained as the collective name of activities that are conducted to reduce the effect of variation (Söderberg et al., 2016).

The manufacturing industry continues to have people in the final assembly of cars, despite the development within automation. Swift and Booker (2013) describe the reason to be that manual assembly is incredibly flexible. During the late part of the twentieth century, the concept of mass-customization was introduced, to describe the increased implementation of personalized products at a mass-produced amount (Tseng et al., 2017). One of the limitations of mass-customization is the increased need for flexibility (Zipkin, 2001). Alford et al. (2000) explain that the risk for the automotive industry with customization is the increasing complexity and cost in the manufacturing. Falck and Rosenqvist (2014) and Falck et al. (2014) state that a higher complexity of manual assembly operations results in more errors made by the operators and consequently a higher cost from fixing those errors. Furthermore, the risk of operator error increased both when the ergonomic load increased and when the complexity increased.

In order to improve the quality of a product, it is beneficial to improve the ergonomics (Eklund, 2001) and this is also advantageous in regards to saving costs (Axelsson, 2000). An interview study allowed both project managers and geometry assurance engineers in design and manufacturing to answer whether they consider ergonomics (Rosenqvist et al., 2012a). Further, the interview study reveals that, although the awareness of the importance of ergonomics was high among the professionals, it was not generally included when choosing which geometry system solution to use. Moreover, geometry assurance does not consider ergonomics while designing the products. Ergonomics is one of 16 criteria affecting the assembly complexity of an assembly operation (Falck et al., 2016). That means that beneficial ergonomics can contribute to decreasing the assembly complexity of an operation.

According to Rosenqvist et al. (2012b), the complexity of manual assembly operations has increased during the last years. Furthermore, the majority of the professionals who were asked in the article state that there is only a low correlation between the physical products that are assembled and the results of the same products from the Computer Aided Tolerancing (CAT) simulation tools. There were some factors most of the study subjects answered to be affecting the geometric quality (Rosenqvist et al., 2012b). The three most predominant answers were whether an assembly had multiple ways to be performed, the operator's posture during the assembly, and the operator's ability to see the operation performed. These are all criteria of manual assembly complexity mentioned in Falck et al. (2016). Therefore, it is concluded to be a need to include assembly factors in CAT-tools (Rosenqvist et al., 2012b). This is further supported by another study, where statistical calculations based on data from companies show a low correlation between physical, assembled products and the CAT simulations (Rosenqvist et al., 2013).

This led to the start of the AMIGO (Analys med manikin för bättre geometrisk kvalitet vid manuell montering, Analysis with a manikin for better geometric quality during manual assembly, [authors' translation]) project, a research project collaboration between Chalmers and several well-known Swedish automotive manufacturers. The purpose of the project is to attain a better product quality, by analyzing the complexity in manual assembly, with the help of a manikin in a simulation environment to improve the geometry assurance (Chalmers, 2019). This can enable opportunities to bring forward tasks earlier in the development phase, which would potentially require fewer resources (Chalmers, 2019). As a result of the AMIGO project the geometry assurance program, RD&T was combined with the program IPS IMMA to be able to see the complexity in manual assembly while designing them. RD&T is a simulation tool that allows the user to conduct a statistical tolerance analysis (RD&T Technology AB, n.d.). Thereby, it is possible to simulate deviations in the assembly. IPS IMMA can use a manikin, which is a biomechanical model of a human, in order to simulate an operator performing assembly work (IPS AB, n.d.). Both RD&T and IPS IMMA are established individual programs within the industry. This can be used to ensure that there is an obstacle free path for assembling a component. The tool includes a function where the path with the least biomechanical load is chosen. The combined RD&T and IPS IMMA program allow the user to make the geometry in RD&T and thereafter the assembly complexity is judged using the IPS IMMA. Therefore, there is a need to validate the added function that assesses assembly complexity with these two programs and investigate how it can be integrated into the product realization process.

1.2 Aim

This master thesis aims to give proposals that can increase quality, robustness, and reduce costs in the product development, by analyzing the simulation tool RD&T combined with IPS IMMA. The program will be evaluated based on its ability to assess manual assembly complexity and how it can be implemented.

1.3 Limitations

In this project, the only software used is RD&T combined with IMMA and the data is collected from only one company. The validation of the simulation program is also limited to studying a specific sub-assembly, which is the rear bumper and rear lamp. The manual assembly production of these articles is in China and therefore the data is secondary collected and the access to additional data is limited.

1.4 Research Questions

The questions under investigation of this issue can be formulated into several research questions.

1. Can the function that assesses the assembly complexity in the combined RD&T and IPS IMMA be validated for the rear bumper and rear lamp?
2. What are the potential improvements for RD&T/IPS IMMA?
3. How can RD&T/IPS IMMA be integrated into the product realization process at CEVT?

2
Theoretical Framework

To provide necessary knowledge about the areas the project covers, this chapter, the theoretical framework, describes more about robust design, geometry assurance, inspection methods, manual assembly, validation, the combined program: RD&T/IPS IMMA, team efficiency, and change management.

2.1 Robust Design

The concept of robust design was developed during the late twentieth century and one of its originators was Genichi Taguchi (Arvidsson & Gremyr, 2008). The purpose was to expand the design concept to include methods to minimize the effects of potential variation in the design phase, that could affect the product quality (Allen, 2010). Robust design is about decreasing the influence variation has on the design (Söderberg et al., 2016).

2.1.1 Costs in Design

Applying a design focus in the product development process can have a considerable impact on the cost and quality of the product (Dieter & Schmidt, 2013). The design phase in itself is not necessarily costly, but the decision taken about the design in this stage has a substantial impact, up to 70-80-%, on the cost later on in the manufacturing (Dieter & Schmidt, 2013). Therefore, it is difficult to make large changes to a product after the design is set, with only 25 % left of the total cost to affect. This can also be related to the freedom paradox within design, where there is little knowledge about the design problem and numerous decisions need to be made (Dieter & Schmidt, 2013). Therefore, when the processes move forwards, the learning increases, but the possibility to change the design decreases, preventing from fully using the new knowledge without extensive costs. It can therefore be of importance in the design process to focus on issues emerging in the manufacturing process.

2.1.2 Taguchi Methods

The focus of the Taguchi method is how to improve quality by decreasing the amount of variation in the system (Dieter & Schmidt, 2013). Before, variation was viewed as something that could be handled in the manufacturing with inspection, but Taguchi brought the design process to the table as a tool (Dieter & Schmidt, 2013). The method is built on factors that influence the variation, these are defined as noise and control (Allen, 2010). Noise factors in manufacturing are hard to manage and costly to handle (Arvidsson & Gremyr, 2008). Therefore, the goal is to make the products insensitive to the noise instead. The control factors are parameters that are controllable in the manufacturing or design process and can be seen as design parameters (Dieter & Schmidt, 2013). Therefore, by adjusting the control factors, the product's reaction to the variability noise factors create, can be decreased.

2.1.3 Axiomatic Design

Axiomatic design is a design theory developed by Suh in the late twentieth century (Kim, 2014). The purpose of it was to implement principles to the design process compared to the previous theory of design based on experience, which could be time-consuming and costly (Suh, 2021b). Axiomatic design is about eliminating unnecessary mistakes and reaching the best design decision faster by clearer defining the problem identified into two questions, *what* and *how* (Suh, 2021b). Thereafter, the answer to *what*, is defined as Fundamental Requirements (FR) and *how* as Design Parameters (DP). The relationship between FR and DP is that DP should answer the question of how to fulfill the FRs (Suh, 2021b). Suh (2021a) describes this relationship in Equation 2.1, with the Design Matrix (DM).

The DM describes how the FR and DP are connected to each other, the design can be seen as uncoupled, decoupled, or coupled. With an uncoupled design, it is one DP satisfying an FR as in Equation 2.2, with decoupled design, the DM is triangular as in Equation 2.3 and with a coupled it is multiple DPs fulfilling one FR, as in Equation 2.4 (Kim, 2014). Central in the axiomatic design are the two axioms, independence and information axiom (Kim, 2014). There the first one is requiring the design to be uncoupled or decoupled and the information axiom is seeking the design with the minimum amount of information.

$$\{\mathrm{FR}\} = [\mathrm{DM}]\{\mathrm{DP}\} \tag{2.1}$$

$$\{\mathrm{FR}\} = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix} \{\mathrm{DP}\} \tag{2.2}$$

$$\{\mathrm{FR}\} = \begin{bmatrix} A_{11} & 0 \\ A_{21} & A_{22} \end{bmatrix} \{\mathrm{DP}\} \tag{2.3}$$

$$\{\mathrm{FR}\} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \{\mathrm{DP}\} \tag{2.4}$$

When the input DPs can affect several outputs of FRs, necessary tuning can become more difficult, for example when tuning the DP so the tolerances are reasonable for the FR, other FRs can also change (Cavique et al., 2021). Suh (2005) describes the complexity in axiomatic design as "a measure of uncertainty in satisfying the FRs" (p. 7). The second information axiom contributes to making the design more robust if it is fulfilled, because it is easier to minimize the amount of information in an uncoupled or a decoupled design, compared to a coupled design (Suh, 2021a).

In an article by Kar (2000), the axiomatic design theory, especially when the information axiom is accomplished, shows a connection to also satisfy the goals of the Taguchi method at the same time. In conclusion, by satisfying the axioms, an easier and more robust design can be achieved. In Söderberg and Johannesson (1999), Suh's axiomatic design is put in the context of how to break or detect tolerance chains in assembly, which can be seen as coupled because of multiple inputs to one output. Therefore, by removing unnecessary tolerance chains, the products have the potential to be more robust after assembly.

2.1.4 Locating Schemes

Locating schemes are designed in order to position a part and can be used to create a robust design (Söderberg et al., 2016). A rigid body has six Degrees Of Freedom (DOF), three DOF go in translational and three go in rotational directions. Therefore, a rigid body can be locked with a 3-2-1 locating scheme.Locating schemes are built by multiple locating points, placed to lock the position of the part (Söderberg et al., 2016). For example, in a 3-2-1 locating scheme, three points in the z-direction locks translation in z, and rotation in x and y. Two points in the y-direction create a line and lock translation in y and rotation in z. The last is a point in the x-axis, that locks translation in x. A nonrigid body can have more DOFs and can be over-constrained. It is important to use the same locating scheme throughout production, to ensure that the geometric variation remains low (Söderberg et al., 2016).

The position of the locating schemes can also be optimized using algorithms (Söderberg et al., 2016), as there are several ways the locator schemes can be placed (Söderberg et al., 2006). It is a common rule that the locator schemes should be spread apart on the part (Söderberg et al., 2016). While performing an optimization it is possible to have different focuses. It is possible to optimize with respect to either the entire component or to critical features.

2.1.5 Stability Analysis

To evaluate the robustness of a concept, it is possible to use a stability analysis (Söderberg et al., 2016). The stability analysis aims to determine how sensitive the final product is to variation caused by the position of the locators. When the stability analysis is conducted the positions of one locator at the time are moved in small steps. The variation in the output points is evaluated by calculating the root sum squared number using the variation in different directions, representing the variation caused by the different locators. At this stage, color codes are used to show whether there is a high or low sensitivity for variation i.e. a sensitive or robust concept in different points. In this analysis, a stability matrix is also generated to show the sensitivities of parts within the concept (Söderberg et al., 2016). Furthermore, the critical features of the product should be located at stable locations to ensure robustness.

2.2 Geometry Assurance

Geometry assurance is the collective name of activities that are conducted to reduce the effect of variation (Söderberg et al., 2016). These activities take place during different phases in the product development process. In the following section, such activities are described. In this section, the words “components” and “parts” of a product are used interchangeably.

2.2.1 RD&T

RD&T is a CAT tool that can support geometry assurance activities throughout the product realization loop, described in Section 2.2.2. The tool supports tolerance analysis by applying statistical variation simulation (see Section 2.2.3) (RD&T Technology AB, n.d.). The aim is to produce robust product concepts that can withstand variation.

2.2.2 Product Realization Loop

The product realization loop consists of three phases: the concept phase, the verification phase, and the production phase, see Figure 2.1 (Söderberg et al., 2006). During these different phases, different geometry assurance activities take place.

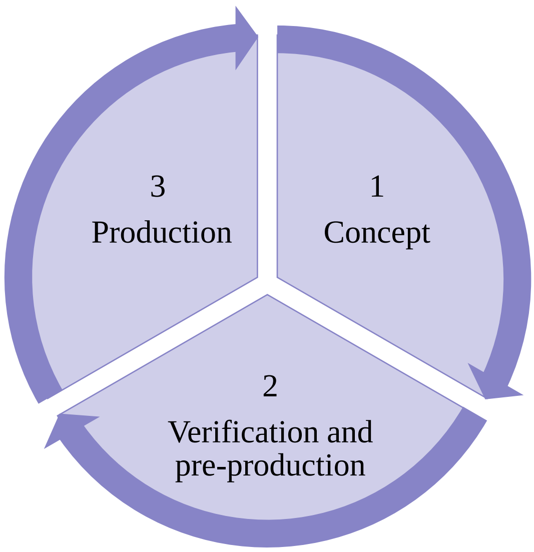

Figure 2.1: Illustration of the product realization loop, adapted from Söderberg et al. (2016).

2.2.2.1 The Concept Phase

The concept phase mainly consists of simulation and virtual testing of the product and manufacturing concept, before any product is realized. In this phase, there are certain decisions regarding the product that are made. The decisions consider which parts of a product should be manufactured separately, the optimal tolerances, for both product and parts, and the most advantageous positions for the locators. These decisions are based on the methods presented in Table 2.1 with short explanations. The information is adapted from Söderberg et al. (2016) and Söderberg et al. (2006).

Table 2.1: This table shows activities in the concept phase with brief explanations.

Activity	**Explanation**
Stability Analysis	A stability analysis can be performed to evaluate the sensitivity of variation on the product, which depends on the placement of the locating schemes. The purpose of this activity is to enable choosing a suitable position of the locators that reduces the effect of variation from manufacturing.
Locating scheme optimization	Optimization algorithms are used to predict the optimal places for the locating schemes, see Section 2.1.4.
Statistical variation simulation	Statistical variation simulation is used to find the variation of important product features (Söderberg et al., 2006). This is further explained in Section 2.2.3.
Part variation estimation and modeling	To estimate the variation of the whole product, it is beneficial to know the variation of the included components. However, since such data is limited in the concept phase, the information is instead gathered through different methods of simulation and modeling.
Split-line analysis	Split-lines are the distances and relations between the components within the product. They are an important feature for the perceived quality. Split-lines can be evaluated by a seam variation analysis, which uses real part variation and Monte Carlo simulation, or by calculating the quality appearance index, which is the mean variation of the measurements of the split-lines and can support perceived quality.
Split-line optimization	In cases where the locator schemes are pre-defined a split-line optimization can take place. Split-line optimization aims to find the optimal spacing between different components, both with respect to function and aesthetics. (Söderberg et al., 2006).
Visualization of variation	A visualization of how variation can affect a component can increase understanding.

Table 2.1 continued from previous page

Activity	Explanation
Tolerance allocation	In order to achieve high quality for a lower cost the tolerances of the parts of a product shall be distributed beneficially. See 2.2.4 Tolerance Allocation.
Joining sequence optimization	The order of joining of the parts can affect the final quality, especially for non-rigid parts. Therefore, joining sequence optimization can be performed to increase the robustness. It is common to use the genetic algorithm as it is a non-linear problem.

2.2.2.2 Verification and Pre-Production Phase

The verification and pre-production phase are the next step after the concept phase. In this stage, the concept is verified before it is prepared for production, involving testing it physically and thereafter solving the mistakes (Söderberg et al., 2006). The main activities involved are inspection preparation and virtual trimming.

2.2.2.2.1 Inspection Preparation and Virtual Trimming

Preparation of inspection implicates the process of deciding inspection points to analyze and gain information about the product in this stage (Söderberg et al., 2016). Multiple different areas use the information from the inspection to improve the product, which can increase the number of data points needed significantly. So to pinpoint where on the product to analyze, different methods can be used such as tolerance analysis, robustness analysis (Söderberg et al., 2016). A helpful method to decrease the number of inspection points and reduce resources is to use cluster analysis, where only one point in the cluster is measured instead of the whole cluster (Wärmefjord et al., 2009). Virtual trimming is applied to optimize the last errors with virtual tools that are discovered when testing the product (Söderberg et al., 2016). This can be performed by refining the locating scheme with iteration and information from the inspection data in a variation simulation model.

2.2.2.3 The Production Phase

In this phase of the loop, the products are produced in the production. The continued work to secure the quality is to proceed to use models from previous phases along with measuring data from the products to ensure beneficial production quality (Söderberg et al., 2016). Two methods to do this are Root Cause Analysis (RCA) and Six Sigma.

2.2.2.3.1 Root Cause Analysis

In the complex setting of an assembly line in the automotive industry, geometrical problems can be difficult to find (Söderberg et al., 2006). An RCA aims to find the root cause of a failure that has occurred to the product (Okes, 2009). There are multiple methods in which the root cause can be found. Among those, there are virtual tools available that are more aimed toward geometry assurance and can include elements such as fixtures (Söderberg et al., 2016).

2.2.2.3.2 Six Sigma

Six Sigma has five steps. The steps are Define, Measure, Analyze, Improve, and Control (DMAIC) (Söderberg et al., 2006). The purpose of Six Sigma includes working towards a reduced variation in processes, conducting a DMAIC framework on certain features, and maintaining a quality improvement focus from the entire organization (Desai, 2010). Desai explains the purpose of the different steps as followed. At the Define step, the issue is defined and questions such as why it is important and who will solve it are also addressed. In the second step, Measure, the current state of the process is measured, and data is collected. In the third step, Analyze, statistical tests are performed in order to find the root cause. The fourth step, Improve, focuses on removing the cause of the issue, that was found in the previous step. Lastly, at the Control step, the process returns to the usual work process, while it is ensured that the issues will not occur again. During the steps of Analyze and Improve, it is possible to utilize a virtual model and to use variation simulation (Söderberg et al., 2016).

2.2.3 Variation Simulation

Variation simulation is used in order to predict the variation of important product characteristics (Söderberg et al., 2006), specifically variation of geometric features (Wärmefjord et al., 2016). There are different reasons why a product can deviate from its nominal value. Two common factors affecting the variation in the final product are variation of the fixtures (or locating schemes, see Section 2.1.4) and variation of the parts (Wärmefjord et al., 2016). Fixture variation depends on the position while operations are performed. Part variation depends on different properties of the manufactured parts, such as the material and previous manufacturing.

The accuracy of a simulation is important in order to achieve a reliable result (Wärmefjord et al., 2016). To achieve good enough accuracy to replace the physical testing, as many of the factors affecting the real-life production as possible should be included in the simulation. Variation simulation can be performed through Monte-Carlo simulation. Monte-Carlo simulation is a method using random numbers to explore how different features can change based on different inputs (Harrison, 2010). A common manner to conduct this is to model the system as a probability density function, with defined input and output, and including an element of randomness. These simulations are commonly repeated to study the results.

While performing a variation simulation of assemblies, they can be viewed as rigid or non-rigid (Wärmefjord et al., 2016). Rigid parts are parts that can be assumed to not bend during assembly and will remain in place when secured by six degrees of freedom. Meanwhile, a non-rigid part can be over-constrained. A simulation of non-rigid parts can be performed by including the finite element analysis.

2.2.4 Tolerance Allocation

In a tolerance allocation, the tolerances of the product are allocated among the components (Söderberg et al., 2016). It can be costly to have tighter tolerances on parts, due to a higher demand on the manufacturing (Söderberg & Johannesson, 1999). A cost allocation can be used to decide where certain tolerances are used. When the tolerance allocation is performed, the design requirements are used to determine the required limit of the containing components (Lööf et al., 2007). There are three suggested strategies for tolerance allocations (Söderberg et al., 2006). The first option is to let the different components contribute equally to the tolerances of the final product. The second option is to optimize with respect to saving cost, by reducing the tolerances on parts where it is possible to reduce the tolerances for a lower cost. The third option is to optimize with respect to both cost and so-called quality loss.

2.2.5 Inspection Methods

Different inspection methods can be used to measure parts and products. The suitable choice of inspection method depends on the selected tolerances. The Gauge Maker's Rule states that the instrument used for inspection should have 10 times better accuracy than the tolerance of the feature being measured (Scallan, 2003). In order to conduct a quality inspection, there are different equipment that can be used. These include manual instruments, such as calipers, micrometers and basic gauges, and digital instruments, such as Coordinate Measuring Machines (CMM), and laser and optical scanners.

The CMM works by utilizing coordinates, which are discrete points in space, to find the form of the object (Scallan, 2003). The machine can then compare the found shape to the desired shape, and thereby inspect whether the component is within the specified tolerances. The CMM can use different types of sensors, which either give contact measurements, such as touch probes, or non-contact measurements, like optical probes (Hexagon, 2022). The other example of digital instruments is scanners. Scanners work by generating a point cloud by sending out and monitoring reflected light pulses. This point cloud can thereafter be compared to the nominal values and thereby showing the deviations of the manufactured parts (Wärmefjord et al., 2017).

The CMM and scanners have different advantages (Matache et al., 2015). The CMM have slightly higher accuracy, lesser requirements on the post-processing, and a possibility to capture the edge geometry of parts. Meanwhile, using a scanner is a faster method and less education is needed for the operator. The benefits also include more surface points, cheaper equipment prices, and access to sophisticated software for post-processing. The properties are considered while choosing measuring techniques.

2.3 Manual Assembly

Manual assembly is defined as assemblies performed with manual methods, where the tasks usually can be identified as picking up a component, moving it to the assembly location, placing it in the right position, and finally securing it in the correct place (Lien, 2014). The process of manual assembly can be supported by mechanized or automated solutions, e.g., tools and how parts are transported (Swift & Booker, 2013). The level of automation can be divided into different categories, describing how much automation is implemented in production. One example is by Frohm et al. (2008), where seven levels are formulated, ranging from manual assembly, where for each level the automation is increased until the last level is for full automation. However, it rarely goes directly from manual to completely automatic.

As described in Section 1.1, manual assembly is still common in the manufacturing industry despite the development of automation. Manual assembly provides increased possibilities of flexibility (Swift & Booker, 2013). This can be seen as a favorable attribute, when manufacturing moves toward mass customization compared to when mass production started in the early twentieth century (Hu, 2013). The concept of mass customization is to produce a customized product at a mass production pace (Tseng et al., 2017). One limitation in manufacturing, when the variety in products is increasing, is that it requires more flexibility (Zipkin, 2001). This can be an explanation for why manual assembly still is common.

2.3.1 Ergonomics

Manual assembly involves the participation of humans, and therefore ergonomics becomes relevant. Ergonomics can be divided into physical, cognitive, and organizational, where cognitive is the mental stress for humans, physical the bodily stress, and organizational shifts the focus on ergonomics from the individual to an organizational perspective in a company (Berlin & Adams, 2017). Ergonomics is important because of its effect the workers' health has on the manufacturing, e.g., unable to work, injured or quits, which can develop costs for the company (Berlin & Adams, 2017). Insufficient ergonomics in assembly can also affect the quality of the products in manufacturing (Falck et al., 2010). In order to be able to analyze ergonomics, several evaluation methods have been developed. Two of them are Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA), developed as a quick manner to find harmful postures (Berlin & Adams, 2017). In both methods, specific postures are evaluated and receive a final score, showing how harmful the posture is. RULA is appropriate for hand-arm intensive work and REBA is developed for whole-body intensive work (Berlin & Adams, 2017).

2.3.1.1 Intelligently Moving Manikin (IMMA)

Digital Human Modeling (DHM), are simulation programs that allow ergonomics to be tested in a virtual environment with digital humans, manikins (Berlin & Adams, 2017). One of them is IPS IMMA, which uses multiple different biomechanical models of humans, and manikins to simulate (IPS AB, n.d.). IMMA is the manikin part of the program and the purpose of the IPS function is to provide a collision-free path for the objects or the manikins (Hanson et al., 2014). With this simulation tool, ergonomics can be analyzed earlier in the development phase of the production system, providing important inputs to the process (Hanson et al., 2014). The IPS IMMA has built-in functions that can perform RULA and REBA.

2.3.2 Complexity Criteria

The relation between complexity in manual assembly and its effect on product quality has been studied by Falck et al. (2017) and has been further developed into 16 complexity criteria. The criteria is divided into 16 High Complexity (HC) and corresponding 16 Low Complexity (LC) criteria, see Table 2.2, (Falck et al., 2017). To prevent the costs of quality errors in manufacturing due to complexity, the criteria can be implemented in the concept phase to increase the awareness of manual assembly complexity earlier in the process (Falck et al., 2016). By implementing it earlier, the added costs of changing a design late in the process can be avoided. When applying the criteria on an assembly, both HC and LC criteria should be used (Falck et al., 2016). The aim is to decrease the HC criteria but to fully avoid quality issues, the LC criteria should also be satisfied.

Table 2.2: Description of the 16 HC and LC criteria, adapted from Falck et al. (2017).

No.	High Complexity	Low Complexity
1.	Many different ways of doing the task	Standardised (accepted) way to do the task
2.	Many individual details and part operations	Few details to mount; preassembly; module solution (integrated assembly)
3.	Time demanding operations	Solutions that are easy and quick to assemble (non-time demanding)
4.	No clear mounting position of parts and components	Clear mounting position of parts and components
5.	Poor accessibility	Good accessibility
6.	Hidden operations	Visible operations
7.	Poor ergonomics conditions implying risk of harmful impact on operators	Good ergonomics conditions implying no harmful impact on operators
8.	Operator-dependent task requiring expert knowledge to be properly done	Non-operator dependent operations not requiring much experience to be properly done

Table 2.2 continued from previous page

No.	High Complexity	Low Complexity
9.	Operations must be done in a certain order/sequence	Independence of assembly order (could only be done in one way)
10.	Visual inspection of fitting and tolerances is required, i.e. careful subjective assessment of the quality output	Standardised assembly. Careful subjective assessment of fitting/tolerances is not needed
11.	Accuracy/precision demanding task	No precision-demanding task, no careful fitting is necessary.
12.	Need of adjustment	No adjustment needed
13.	The geometric environment has a lot of variation ('tolerances') meaning the level of fitting and adjustment varies between the products	Easy fitting, self-positioning parts/components that can be controlled in three dimensions: X, Y and Z
14.	Need to have in detail described work instructions	Self-evident operations that do not need clearly written instructions
15.	Soft and flexible material	Form-resistant material that does not change shape or form during assembly
16.	Lack of immediate feedback of properly done work, e.g. by a clear click sound and/or compliance with reference points	Immediate feedback of proper installation e.g. by a clear click sound and/or compliance with reference points

2.4 The Combined Program: RD&T/IPS IMMA

As mentioned in Section 1.1, the RD&T/IPS IMMA consists of a combination of the two simulation programs, where it is possible to reach IPS IMMA directly from RD&T through an automatic function, where an analysis of manual assembly complexity using a manikin can be made, see Figure 2.2. Currently, it is a beta version, which is planned to be developed for use within the industry. Before the analysis is run, the planning geometry, obstacle geometry, vision point, and assembly direction are specified. The planning geometry is the article that will be assembled during the analysis. The obstacle geometry is the article or articles that the planning geometry shall not collide with. After the information is defined, a simulation can be made, and the result is presented in the window that is shown in Figure 2.3. The result is given through the 16 assembly complexity criteria that are assessed to be either evaluated high or low. Based on the results of the assembly complexity criteria from the simulation, a complexity score is received, which is a normalized number between 0 and 1. The program also allows the user to conduct a stability analysis (see Section 2.1.5), that gives a normalized answer between 0 and 1. Thereafter, the statistical number Root Mean Square (RMS) can be calculated from these numbers. That gives a value called SUM (RMS) in Figure 2.3, that is based on both the robustness and the assembly complexity (Rosenqvist et al., 2014).

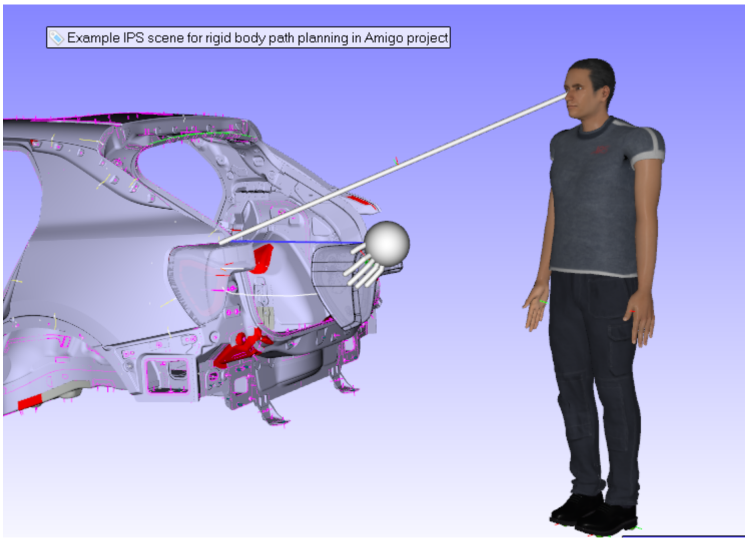

Figure 2.2: The manikin assembling in the IPS IMMA environment in the combined RD&T/IPS IMMA.

The assembly complexity criteria that are used in the program are the ones presented in 2.2. However, at this stage not all criteria are possible to assess within the program. The criteria that are currently judged by the program are one, three, five, six, seven, nine, and eleven, and J. Nyström (personal communication, April 28, 2022) has explained how those criteria are assessed and it is described below.

- Complexity criterion one, *many different ways of doing the task*, is judged based on the number of articles that is part of the operation, which in this version is one.
- Complexity criterion three, *time demanding operations*, is judged based on the time between the grip is finished and the assembly operation is finished. If that time is longer than 105 Time Measure Unit (TMU), the criterion is assessed as high complexity.
- When complexity criterion five, *poor accessibility*, is assessed, a sphere with a radius of 8 cm is generated. This sphere is checked for collision with the obstacle geometry. If there is a collision during the assembly operation, the criterion will be set to high complexity.
- Complexity criterion six, *hidden operations*, is judged using the vision point. If the line between the manikin's eyes at the starting position and the previously defined vision point on the object that shall be assembled, is cut through any of the obstacle geometry, the complexity is high.
- Complexity criterion seven, *poor ergonomic conditions implying risk of harmful impact on operators*, is high when the RULA point is more than 0.

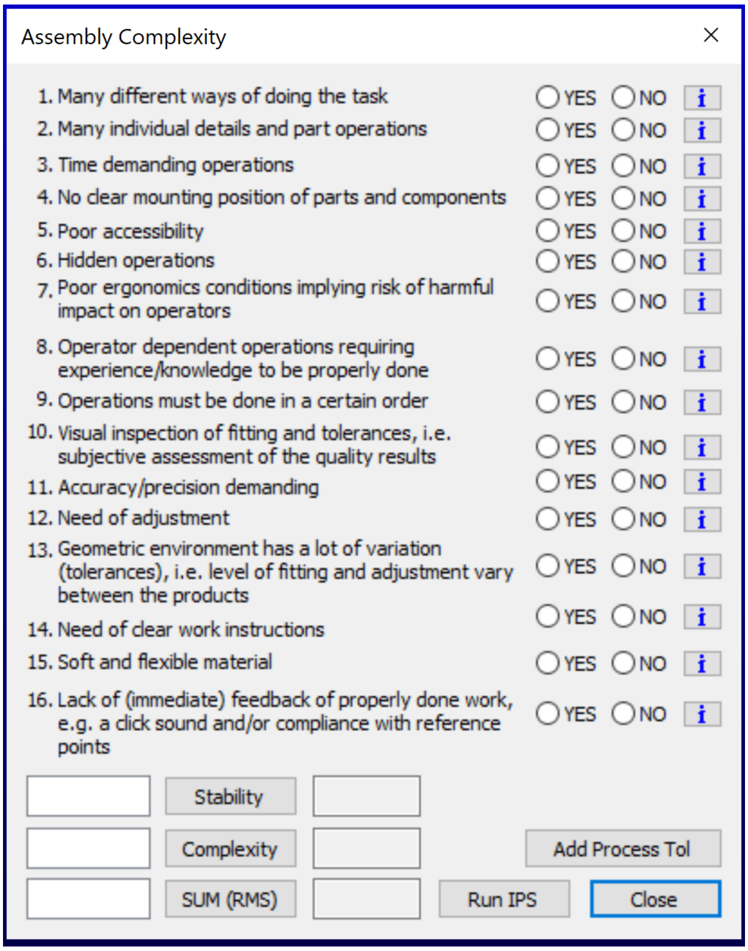

Figure 2.3: The window showing the results in the combined RD&T/IPS IMMA.

- Complexity criterion nine, *operations must be done in a certain order/sequence*, return the opposite to criterion one, *many different ways of doing the task*.
- Complexity criterion eleven, *accuracy/precision demanding task* is high if the start position of the object is 5 m or more from its end position. In the current version, there is no specific manner to measure especially high requirements of fine motor skills or precision.

2.5 Verification and Validation

In order to ensure that a simulation model is functioning accurately, there is a need for verification and validation (Sargent, 2010). Verification includes ensuring that the aspects of a process comply with what actually occurred (Given, 2008). Furthermore, validation refers to how appropriate it is to utilize a model for a purpose (Frey, 2018). Schlesinger et al. (1979) writes that SCS TECHNICAL COMMITTEES has founded terminology, including definitions for model validation and model verification. Verification can be defined in the following manner: "Substantiation that a COMPUTERIZED MODEL represents a CONCEPTUAL MODEL within specified limits of accuracy" (Schlesinger et al., 1979, p. 1). Meanwhile, validation can be defined as follow: "Substantiation that a COMPUTERIZED MODEL within its DOMAIN OF APPLICABILITY possesses a satisfactory RANGE OF ACCURACY consistent with the intended application of the model" (Schlesinger et al., 1979, p. 1). Sargent (2010) mentions some intermediate steps in the process of verifying and validating a model. These are conceptual model validation (ensuring that the conceptual model is reasonable regarding reality), computerized model verification (ensuring that the conceptual model is accurately implemented), and operational validation (the model complies with reality with the specified accuracy).

It is important to ensure that the model answers every question that it aims to, the model needs to be validated regarding each question (Sargent, 2010). For the model to be considered accurate it must be valid for each question and also for each set of experimental conditions, following the requirements.

Different methods can be used for validation (Sargent, 2010). One of these methods is *event validity*. In event validity, the outcome from the simulation program is compared to the output from the real system. Another method is *comparison to other models*, where the results of the simulation program are compared to the output of another, previously validated simulation program. *face validity* is a method where experts within the same area are asked whether the results of the simulation program are reasonable. A *Turing test* when experts are asked to tell the difference between the output of the system and the result of the simulation program. If experts cannot tell the difference, the method is considered valid.

2.6 Team Efficiency

There are different definitions of what is meant by a team. Cameron and Green (2020) presents examples of definitions of a team, which appear to have the elements in common that a team consists of two or more people, who together have an aim or responsibility to reach a goal or an outcome. Within a team, certain factors make teams more effective while working. These are having clear goals and feeling purpose, knowing their own role and the roles of the team members, having defined processes and beneficial relationships and communication within the team, and being well-connected to other teams (Cameron & Green, 2020). Firstly, when a team has goals and purpose, they can plan and organize their work to achieve them. Furthermore, role clarity and logical structures facilitate working towards goals. Moreover, the elements that need to be defined in the processes include meetings, rules, awareness on how to handle decisions, problems and reviewing, and how to handle conflicts and rewards. Lastly, communication within the teams is important to be able to achieve the first points and to achieve beneficial results in an organizational structure, communication among other teams is also important.

2.7 Change Management

Zimmer (2021) defines change management as “the deliberate effort to bring one or more individuals’ internal attitudes toward change into closer alignment with the changes happening to them and around them.” There are different models for change management, that break it down into steps. In this section two are presented, one that is founded by Kotter and one that is founded by Cumming and Worley.

The model that is founded by Kotter has eight steps of accelerators that facilitates leading a change (Cameron & Green, 2020). The steps are the following:

- Create a sense of urgency to achieve a change (Apperbaum et al., 2012). Ensure that the company shall feel a need to change by for example referring to potential crises or opportunities.
- Build a guiding coalition (Apperbaum et al., 2012). The guiding coalition should include people with different kinds of “power” within the organization.
- Create a vision for the objective of the change and a strategy showing how the company shall successfully implement it (Apperbaum et al., 2012).
- Communicate the vision to all affected. The use of as many forms of communication as is available is recommended.
- Empower action towards the change by involving people (Apperbaum et al., 2012) and remove obstacles that may hinder the change (Cameron & Green, 2020).
- Create short-term wins by recognizing goals that are achieved through the change and the effort from people working towards it (Apperbaum et al., 2012).
- Continue building on the change (Apperbaum et al., 2012). Do not claim that the change is completed (Cameron & Green, 2020), but continue to build on the success and involve more people.
- Changes should be anchored within the culture to ensure that the change lasts long-term and that the company does not change back to previous manners (Apperbaum et al., 2012).

Another model of change is Cumming’s and Worley’s model, which has five steps (Kondalkar, 2009). The steps on the list are the following:

- Motivating change: Make the organization ready for the change, show the need and advantages och involve people from an early stage
- Creating a vision: Create a realistic vision showing how things will work after the change, backed up by the company’s purpose.
- Developing political support: Assess own power and key players whose support is needed for the change. The key players need to be persuaded.
- Managing the transition: This is the process of going from the old manner of working to the new. In this stage, *activity planning* and *commitment planning*. Activity planning includes checklists, a sequence of activities, and the responsible people. Meanwhile, commitment planning involves getting support from key players contributing to the change.

- Sustaining momentum: In order to sustain the momentum from the change activities like progress meetings, meeting with experts, etc. should take place.

3
Methods

The research strategy for this master thesis is a case study, divided into three phases. A case study approach provides the opportunity to study a specific setting with specific limits (Denscombe, 2014). It can also introduce deeper knowledge about the reason why something is happening compared to only concluding that it is occurring. This approach is connected to having a holistic view of the research, where studying a part can contribute to the whole (Denscombe, 2014). In a case study, multiple different methods can be used to answer the research question and it can even be an advantage, to provide an in-depth understanding of the case (Denscombe, 2014).

The master thesis can be divided into three different phases, see Figure 3.1. In the preparation phase, a literature study was performed, and the project was defined. Thereafter it continued with the implementation phase where the case study was conducted. In the case study, the validation in RD&T/IPS IMMA was performed, and the interviews were conducted. The research process is concluded with an analysis phase of the quantitative and qualitative data.

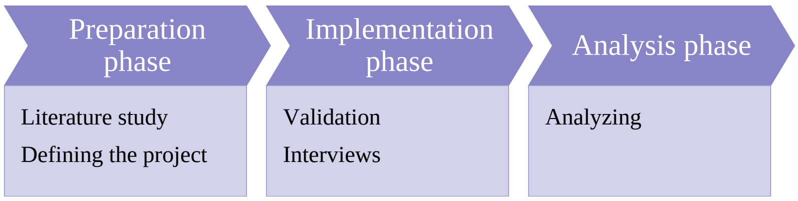

Figure 3.1: Illustration over the research process in this master thesis.

3.1 Literature Study

A literature study was performed in the preparation phase of the project to provide information about the area of study. The areas studied were robust design, geometry assurance, manual assembly, inspection methods, verification and validation, team efficiency, and change management. Information was gathered by using search engines, specializing in academic literature, and articles connected to the research project AMIGO. Search engines used were Google Scholar and Chalmers library. In order to find information, keywords related to the area were selected, examples of these can be seen in Table 3.1. Literature was also examined through the searched articles' references, to access the original source of information. When selecting sources, the sorting process was firstly based on titles and thereafter the abstracts were read to determine if a source was suitable or not for this literature study.

Certain steps were taken to ensure the quality of the information. The first was to look at the number of citations of the publication and the second was whether the authors were recognized from previously read articles. In the literature review, the original source was not always available to access, and therefore secondary sources or later work of the same authors was used.

Table 3.1: List of keywords within the literature study's search area.

Search area	Keywords
Robust design	Axiomatic design Conceptual design Information and freedom paradox Locating scheme Taguchi method
Geometry assurance	Product realization loop Six Sigma Tolerance allocation Variation simulation
Manual assembly	Assembly complexity Digital Human Modelling (DHM) Ergonomics Flexibility Level of automation Mass customization Mass production
Inspection methods	3D scanning Coordinate Measuring Machine (CMM) Laser scanner Measuring techniques Optical scanner
Verification and Validation	Simulation program validation Verification Validation
Team Efficiency and Change Management	Change Management Change Management Models

3.2 Case Study

The research strategy was to conduct a case study at the company. The quantitative approach was performed with data from the company and the qualitative research was performed with interviewees connected to the company or the AMIGO project. In the validation, the assembly process of the rear bumper and the rear lamp of a car from the company were analyzed. The manual assembly operation for the rear lamp in the production is to move the rear lamp from its storage location to position it into its right place in the car, with the help of guiding pins. Thereafter the operator needs to bend into the luggage to fasten the lamp from behind. For the bumper, two operators are needed to press the bumper into its hidden clips and thereafter fasten the bumper from below.

3.2.1 Validation

For the validation of the program, the method *event validity* was used, see Section 2.5, which means that a comparison is made between the results of the system and the real results. Previous data from a manual evaluation performed by the company was used, where ergonomists and representatives from the geometry department conducted a complexity analysis on the case study. This manual assessment was performed with assembly instructions and by viewing film clips of the assembly. The result from their manual assessment of the rear lamp and bumper is presented in Table 3.2, with a comment on why it is considered an HC. The assessment for criterion five, *poor accessibility*, was considered uncertain in the manual assessment. The manual assessment was compared to the simulation results, made by the new combined simulation program of RD&T/IPS IMMA.

Table 3.2: The complexity criteria for the manual assessment for the bumper and the rear lamp.

Criteria	Rear lamp	Bumper	Comment
HC 1	No	No	
HC 3	No	No	
HC 5	Yes	No	Potentially HC, when fastening of the lamp
HC 6	No	Yes	The clips for the bumpers are hidden
HC 7	Yes	No	Bent/twisted work position in the luggage
HC 9	Yes	No	Fastening of the lamp
HC 11	No	Yes	Assembling of the bumper

3.2.1.1 Implementation and Analysis of the Validation

In this section, it is described how the validation was implemented in the combined program. Firstly, the new version of RD&T and the file with the car geometry including the bumper and rear lamp is opened. The function *assembly complexity* is used to open the menu with the sixteen criteria, where the result of the simulation is presented afterward. From here, the menu *assembly path planning* is opened, see Figure 3.2. The bumper or the rear lamp is selected to be assembled on the vehicle with the manikin, called the *planning geometry*. The rest of the articles that you want in the simulation are picked as *obstacle geometry* and the path planning cannot go through it. For the rear lamp, only the body in white was used as obstacle geometry. For the bumper, the body in white, both left and right rear lamp, both left and right body side outer, both left and right water channel and the rear end panel were obstacle geometry.

The assembly direction and vision point can be decided automatically or by selecting points in the system. The assembly direction was automatically decided for both the automatic and manual simulation. The automatic vision point was used for the automatic runs and manually selected for the manual simulation. The last step was to decide which hand to assemble with, either left, right, or both hands. For the automatic simulation, all three different hand grips were tested two times and for the manual simulation, two runs were performed. In the manual run of the lamp, the grip selected was to use one hand, the left hand on the left lamp. Furthermore, in the manual run of the bumper, both hands were used for the grip, because of the size of the article. The grip was placed so that the article would be pushed into its place in a logical standing position for the manikin.

Thereafter, there are two options, *run IPS manually* or *run IPS planning*, which open the software IPS IMMA and automatically load the articles and the path for assembling the article. In run IPS manually, the grip is manually decided and adjusted, but in run IPS planning, the grip is decided by the program. The article is then in the simulation environment in IPS IMMA assembled by the manikin from a decided start position to its assembled position on the car. This is the only movement performed by the simulation in IPS IMMA. The result is thereafter loaded back into RD&T where the sixteen complexity criteria are answered yes or no if fulfilled. Currently, the version of the program provides answers for complexity criteria, one, three, five, six, seven, nine, and eleven out of sixteen.

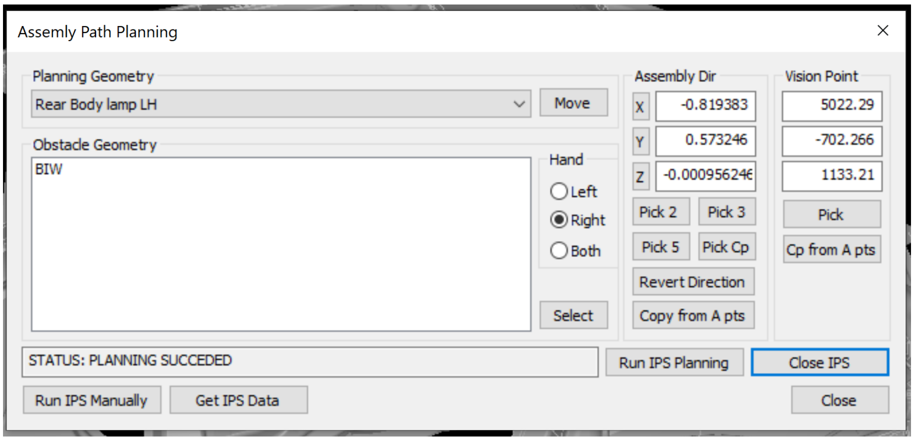

Figure 3.2: Figure for how the assembly path planning window look in the program.

The analysis was performed by comparing the answers in the simulation to the result from the manual assessment for the assembly complexity of the rear lamp and bumper.

3.2.2 Interviews

Interviews were conducted in the case study to collect qualitative data. The selected interview method was semi-structured interviews. Compared to quantitative methods, this was to enable input from the perspective of the interviewees instead of the researcher (Bell et al., 2019). Semi-structured interviews are flexible but rely on prepared questions and allow follow-up questions regarding what is discussed (Bell et al., 2019).

3.2.2.1 Implementation of the Interviews

The selection process was done with purposive sampling, choosing interviewees that have the potential of answering the research questions (Bell et al., 2019). The interviewees were from the company where the master thesis was performed. Based on the research questions, four groups of people were identified to interview, all having a connection to geometry and manufacturing. These were:

- People working with RD&T
- Ergonomist or people working with IPS IMMA
- User of ergonomic/geometry information
- Designers

From these four groups, eleven people were selected to be interviewed. Firstly, the division was four from *people working with RD&T*, two from *ergonomist or people working with IPS IMMA*, three from *user of ergonomic/geometry information* and two *designers*. This sectioning was changed after the interviews were performed, to better match the groups within the work organization. Two of the interviewees were initially placed in user of ergonomics/geometry information but were instead grouped together with people working with RD&T, because they work in the geometry department, and the group was renamed geometry. The group ergonomist or people working with IPS IMMA was instead called manufacturing because the participants are a part of the manufacturing feasibility department. The designers retained their name, as they work in design departments. The group user of ergonomic/geometry information changed to Perceived Quality (PQ), to better describe the interviewee remaining in the group. In Table 3.3, the interviewees are listed and divided into the changed four groups. In the table, each interviewee is assigned a shortening, which is how they are referred to in the result. The interview time was decided to one hour and the location was mixed between online and in person, to facilitate for the interviewees. The prepared interview questions were organized into five categories. Each group can also be called an "attribute", which means they are responsible for a specific property of the final product, such as perceived quality, manufacturing feasibility, or geometrical quality. The categories are:

- Introduction

- Work tasks and work process
- Communication
- Assembly complexity
- RD&T/IPS IMMA

Within these categories, questions were formulated which included follow-up questions. The introduction covered basic questions about the interviewees. In the next category, an overview of the interviewees' work tasks and work process was asked for, e.g., deliveries, meeting structure, and recipient of the result. In communication, the communication between the different groups is examined, specifically focusing on geometry and manufacturing. In the fourth category, assembly complexity, the interviewees' definition of the term is established, and if the connection between geometric quality and ergonomics exists or is considered. In the last category, the combined program of RD&T/IPS IMMA is discussed with a focus on a possible inclusion in the work process and wanted functions. The full list of prepared questions can be found in Appendix A.

Table 3.3: Description of the interviews in the case study.

Interviewees	Short
Geometry	G1
	G2
	G3
	G4
	G5
	G6
Manufacturing	M1
	M2
Perceived quality	P1
Designers	D1
	D2

From an ethical perspective, it is important to keep people's integrity and privacy. Therefore, it is essential that the result reflects the interviewees' responses and intentions. The documentation of the interviews was done by taking notes and recordings, to have the opportunity to listen afterward if the notes were unclear. Before the interview started it was asked if it was allowed to record for the purpose of using the information in this master thesis. If an interviewee asked not to be recorded, only notes would be used. In the report, the interviewees are also anonymized.

3.2.2.2 Interview Analysis

The analyzing process was divided into different steps and based on a qualitative method of coding, see Figure 3.3. The first step performed was to listen through all interviews and adjust the notes accordingly, to ensure the notes were correct. It was decided to not do exact transcripts, but detailed notes in favor of conducting more interviews because of the time-consuming part of transcribing. The second step was to start coding, which was done by highlighting relevant information and describing the information in the margins of the document notes. The pieces of information that were considered relevant were answers to the questions, statements that the interviewees repeated or indicated as important, and information connected to the research questions.

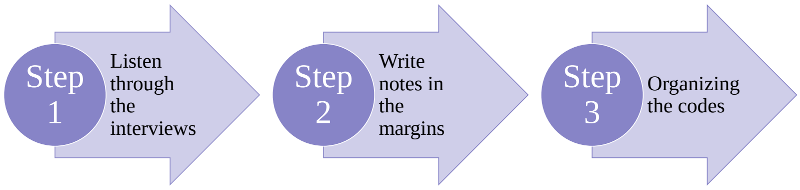

Figure 3.3: Visualization of the analysis of the interviews.

In the third step, the codes were organized as presented in Figure 3.3, and the answers to the different categories in Section 3.2.2.1, were analyzed by category or question. The codes were sorted into first, second, and third order codes, and the hierarchy of the codes is visualized in Figure 3.4. The first order codes are the codes that were written in the margins of the notes from the interviews. The second order codes are the result of first order codes grouped together, sorted while either considering the groups or not. The second order codes were sorted into third order codes in two ways, either by the specific question asked or by a theme that multiple second order codes had in common. The result of the analysis of the interviews was presented by using both tables and bar charts. Tables for the questions with a qualitative approach and bar chart for questions with a quantitative approach. The secondary codes are the information presented in tables in the result.

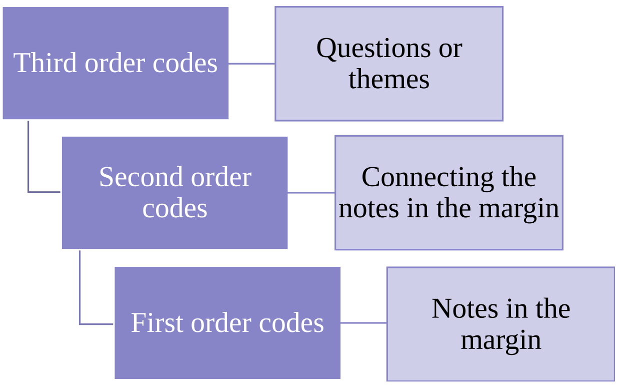

Figure 3.4: Visualization of the hierarchy of codes.

The analysis of the different categories was performed in the following manner. The questions in the introduction category were used as background information to form an overview of the interviewees' backgrounds with the simulation programs.

The questions in the category work process were used to form an overview of the interviewees' work process, meetings, and the interaction between the groups. Furthermore, the gates that were especially important for the different interviewees were mapped. In the analysis of the communication, the second order codes were further sorted by which group the interviewee belonged to, and the third order codes after the interview questions. The codes from the answers from the category assembly complexity were divided by question for the third order codes. The third order codes from the category RD&T/IPS IMMA were sorted by themes. These themes were functions, responsibility, benefits, drawbacks, reflection, potential application, and inclusion.

4
Results

In the following chapter, the obtained results of the project are presented. Firstly, a background of the interviewees is presented together with reflections from the interviewees regarding manual assembly complexity. Thereafter, the validation of the program, potential improvements, and finally the current work process are described.

4.1 Background to the Interviews

In this section, information about the interviewees' prior knowledge about the AMIGO project, RD&T, IPS IMMA, the combined program, and assembly complexity is established.

4.1.1 Interviewees Knowledge about the Program

In the introduction of the interviews, the interviewees were asked if they had heard about the AMIGO project beforehand. Of the eleven interviewees, five had heard about the project before their interview and six had not, see Figure 4.1 for the division between the groups. The interviewees were asked about their knowledge within the existing program of RD&T and IPS IMMA, and if they work or have worked with any of them. The result is presented in Figure 4.2, where the highest knowledge is within RD&T. It was also established whether the interviewees had tried the combined software before the interview. In Figure 4.3, it is presented that none of the interviewees had tried the program, but two of them had seen demos of it before the interviews.

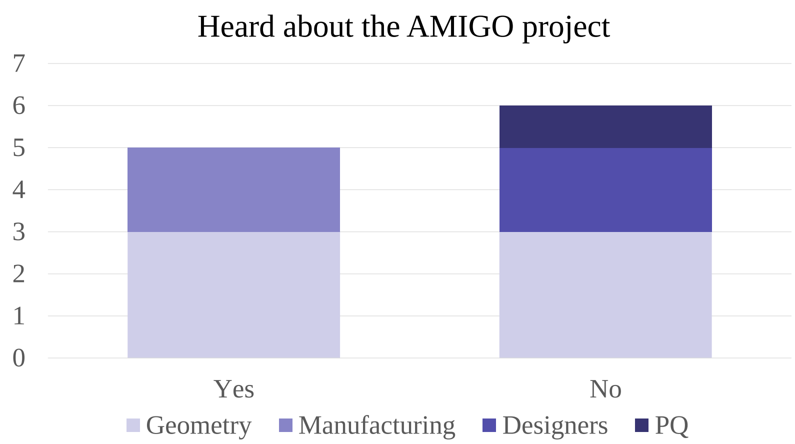

Figure 4.1: The bar chart represents if the interviewees had heard about the AMIGO project before their interview.

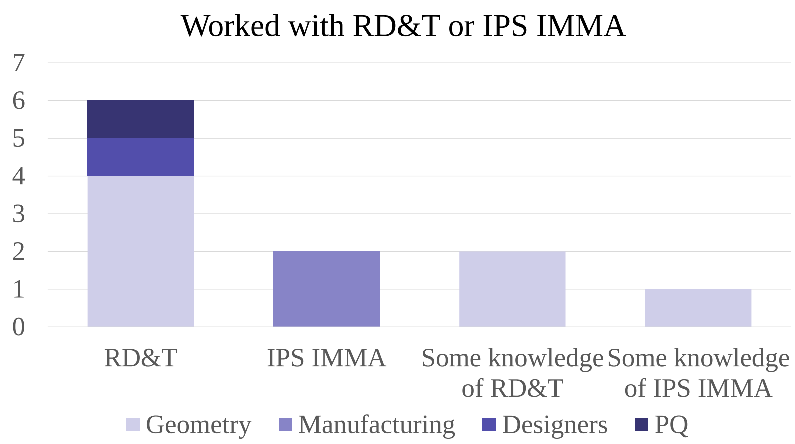

Figure 4.2: The bar chart represents the distribution of the interviewees knowledge about RD&T and IPS IMMA.

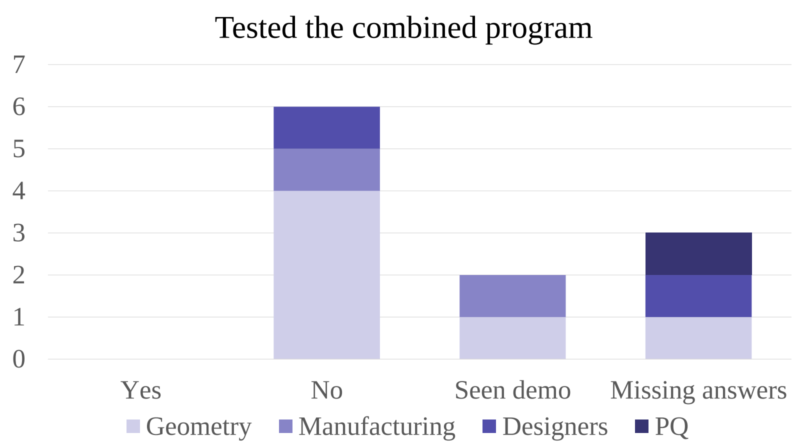

Figure 4.3: The bar chart describes if the interviewees had tried the combined program RD&T and IPS IMMA.

4.1.2 Manual Assembly Complexity

During the interviews, the interviewees were asked questions about their views on manual assembly complexity and whether they included it in their work. Firstly, the interviewees were asked about how they would define manual assembly complexity in their own words. In Table 4.1, the second order codes from their own definitions are presented, and to the right in Table 4.1, the letters represent which of the interviewees answered it. The G is someone from geometry, M means manufacturing, D represents someone from the design department and P is an interviewee from PQ. Thereafter, the interviewees were asked whether they consider their own definitions in their work. Their answers are shown in Figure 4.4.

Table 4.1: Description of the interviewees own definition of assembly complexity.

Second order codes	Mentioned by
How easy it is to assemble the product	G D M
Difficult to assemble, and does not fulfill the requirements	G P
More parts than needed with small tolerances	G G
A combination of factors that may cause the operator to find the operation difficult	G M
Important to ensure that the product cannot be assembled wrongly	D
Do not know what it means	G

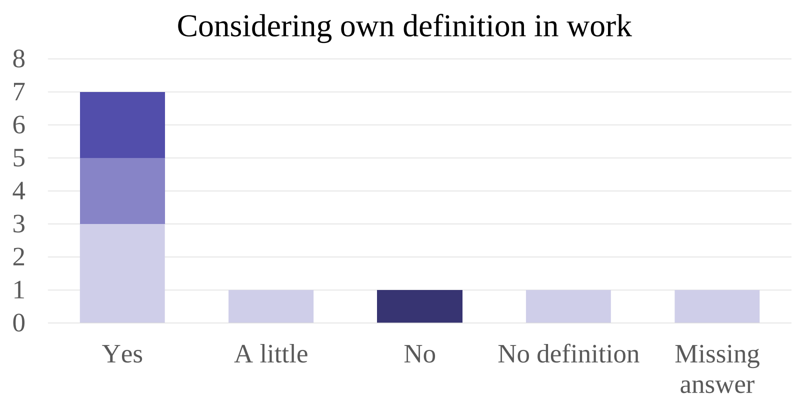

Figure 4.4: The bar chart represent how many of the interviewees consider their own definition in work.

After the interviewees had given their own definitions, the definition of manual assembly complexity used in this master thesis project was presented to them. The definition used in the master thesis was based on the literature study and not the definitions that the interviewees suggested. The interviewees were then asked whether they consider the definition used in the master thesis in their work, see Figure 4.5. The manual assembly complexity definition used in this thesis was:

> *When we speak of manual assembly complexity we mean specific factors that increase the likelihood for the operator to make mistakes. The factors increasing the manual assembly complexity have been divided into 16 complexity criteria in previous research. The basic complexity criteria include criteria regarding how much knowledge is required from the operator, the variety of fitting demands, the number of options of which the assembly can be done, how concentration or memory-intensive the tasks are, and how physically and visually demanding the tasks are.*

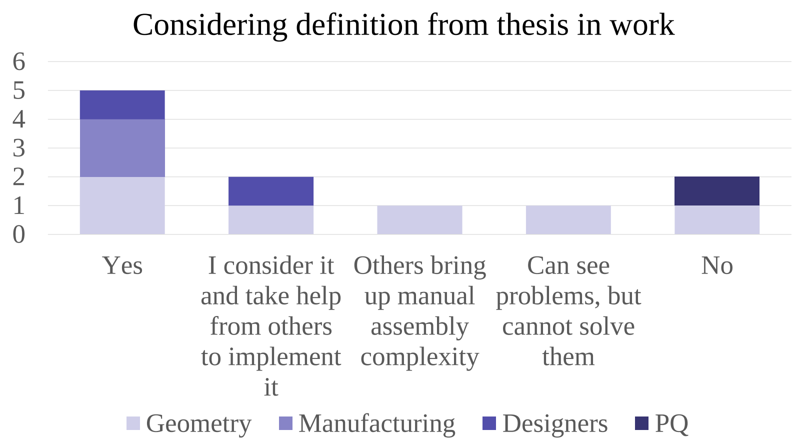

Figure 4.5: The bar chart describes whether the interviewees consider the definition from the thesis in their work.

Furthermore, the interviewees were asked whether there is a connection between ergonomics and geometrical quality. Their answers are presented in Figure 4.6. They were moreover asked to describe the connection. Their descriptions of the connection are compiled in Table 4.2. The most common answer was that bad ergonomics makes the operators take shortcuts. Moreover, the second most common answer was that an easier assembly leads to better quality or that operator difficulties decrease the quality. Furthermore, it was also suggested that the connection is related to a lack of a repeatable system and that, for example, the robustness of fixtures affects the connection. Moreover, it was mentioned that because of geometric requirements, more manual adjustments are needed to fulfill them. That is connected to ergonomics since a human operator will perform the adjustments.

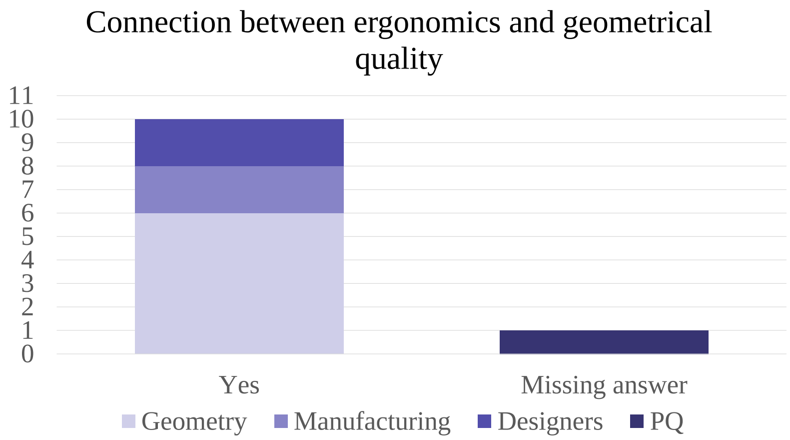

Figure 4.6: The bar chart describes whether the interviewees think there is a connection between ergonomics and geometrical quality.

Table 4.2: The codes describes the interviewees answer to what the connection between ergonomics and geometrical quality is.

Second order codes	**Mentioned by**
If there is disadvantageous ergonomics the operator might take shortcuts, which is bad for the quality	G G G G M
Easier assembly leads to better quality	G D D M
It might relate to the system not being repeatable	G
There might be a need for more manual adjustment because of geometric requirements	P

In addition, the interviewees from the different departments were asked how they are working with this connection and their answers can be seen in Table 4.3. The designers answered that they do it by including both geometry and the manufacturing feasibility department in their design process. From geometry, the answers were more divided. Two interviewees work with the connection by using their own experience with what is beneficial assembly ergonomics, as there is no standardized work process for it. Two of the interviewees said that they do not work with it themselves. However, it comes up in meetings in which they participate, but they do not pursue the issue. Another interviewee states that it is part of the job to develop the guiding features and thereby reduce the complexity for the operator while achieving good calculations. The last interviewee from geometry states that it is manufacturing feasibility that pushes the ergonomics issues. However, every individual can choose what to include in their work. In the interviews with the manufacturing engineers, one of them answered that they work with this connection by having tight discussions and information exchanges with geometry. Meanwhile, the other said that currently it is little collaboration between the two functions. The interviewee from PQ said that working with such a connection is not within the scope of the PQ work role.

Two of the interviewees from geometry were asked whether they had seen any problems due to the potential connection between geometrical quality and assembly ergonomics. The answers stated that they have had to accept a sub-optimal geometry system because the ergonomics need to be improved. Furthermore, it is said that if a geometry system is good, it will be less affected by such a connection, compared to a bad geometry system, that will be easily affected.

Table 4.3: The codes describes the interviewees answers to how they work with a potential connection between assembly ergonomics and geometrical quality.

Group	Second order codes	No. of mentions
Designers	Includes both manufacturing feasibility and geometry in the design	2
Geometry	Use experience to work with the connection	2
	Do not normally work with it, though it can come up in meetings	2
	Part of job to include guiding features that facilitates assembling to the right place and thereby achieve good calculations	1
	ME pushes the development and the individuals choose what they want to include	1
Manufacturing engineers	Having tight discussions and information exchanges with geometry	1
	Currently too little collaboration between IPS IMMA simulations and variation simulations	1
PQ	Not within the scope of the role	1

4.2 Validation

In this section, the result of the simulation of the rear lamp and rear bumper in the combined RD&T/IPS IMMA program is presented. The result is compared to the manual assessment of the rear lamp and bumper in Table 3.2. Both the rear lamp and the bumper were tested with the automatic and the manual simulation function in the program. For the automatic function, the result of using the left hand, the right hand, and the use of both hands is presented. For the manual simulation the optimal grip was used. In the simulation, the manikin moved the article from the decided starting position to the final ending position on the car.

4.2.1 Rear Lamp

For the simulation of the rear lamp, eight runs were successfully run. Six for the automatic simulation and two for the manual simulation. The automatic simulation can be divided into two runs for the left hand, two for the right hand, and two with both hands. The vision point for the automatic run was on top of the rear lamp. Two runs were made where the grip and vision point were manually chosen. The vision point is visualized with a cylindrical line between the manikin eyes at the starting position and the vision point on the article. The grip and the vision point for the first manual run are presented in Figure 4.7. The vision point was on top of the article and the grip was made with the fingers pointing upwards, slightly tilted to the left, from the manikin's point of view. With the second manual run, see Figure 4.8, the grip was positioned with the fingers pointing downwards with a slight tilt to the left. The vision point was placed on top of the rear lamp.

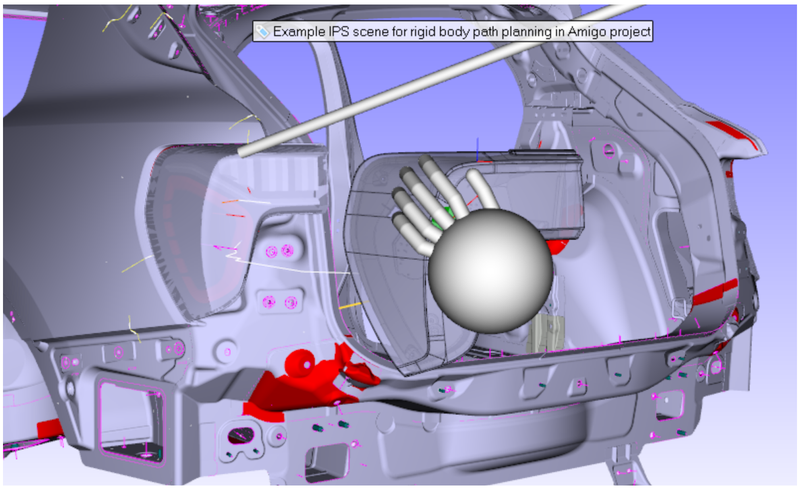

Figure 4.7: Screenshot of the hand position of the left hand and vision point for the first manual simulation of the rear lamp.

The result of the eight simulated runs is presented in Table 4.4. For the automatic simulation, the answer is the same for all rounds except for the second run with the right grip, where HC criterion five, *poor accessibility* is not fulfilled. If there is a difference between the manual assessment for the rear lamp in Table 3.2 and in the simulation, the cell is colored red in Table 4.4. The two criteria that differ from the manual assessment for the automatic simulation are HC criterion three, *time demanding operations* and HC criterion six, *hidden operations*. For the manual simulation, the first run differs the same as the automatic simulation, with criteria three and six. For the second run, it is criteria three and five instead. The result of the comparison between the simulation and the manual assessment for the rear lamp is therefore that four to five out of seven criteria are the same as the manual assessment.

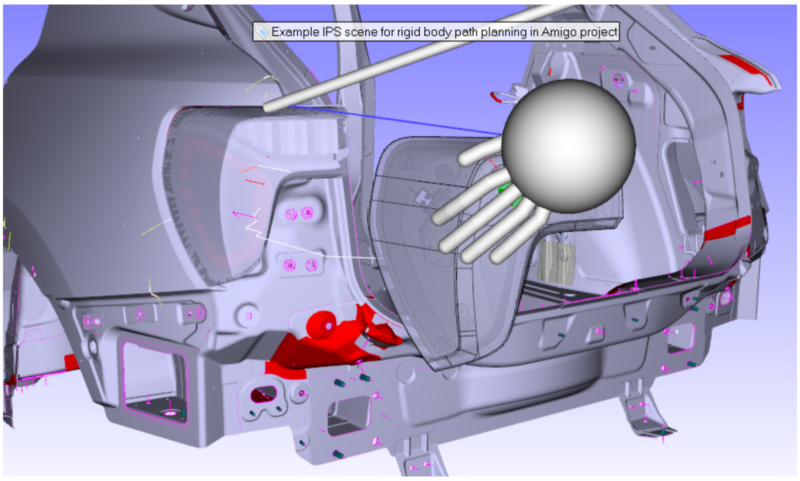

Figure 4.8: Screenshot of the hand position of the left hand and vision point for the second manual simulation of the rear lamp.

Table 4.4: The complexity criteria result for the automatic and manual simulation of the rear lamp. If the simulation differs from the manual assessment the cell is colored red.

Simulation	Grip	HC 1	HC 3	HC 5	HC 6	HC 7	HC 9	HC 11
Automatic	Left	No	Yes	Yes	Yes	Yes	Yes	No
		No	Yes	Yes	Yes	Yes	Yes	No
	Right	No	Yes	Yes	Yes	Yes	Yes	No
		No	Yes	No	Yes	Yes	Yes	No
	Both	No	Yes	Yes	Yes	Yes	Yes	No
		No	Yes	Yes	Yes	Yes	Yes	No
Manual	Both	No	Yes	Yes	Yes	Yes	Yes	No
		No	Yes	No	No	Yes	Yes	No
Manual assessment		No	No	Yes	No	Yes	Yes	No

4.2.2 Bumper

For the bumper, six simulations were done with the automatic simulation function, two with the left hand, two with the right hand, and two with the use of both hands. The vision point for the automatic simulation was on the top of the right side. The same grip was used in both manual simulations. Both hands were used with the fingers directed downward and were placed on the left side of the bumper. The vision point for the manual run was on top of the bumper in the middle. See the grip and vision point for the manual simulation in Figure 4.9 for run one and Figure 4.10 for run two.

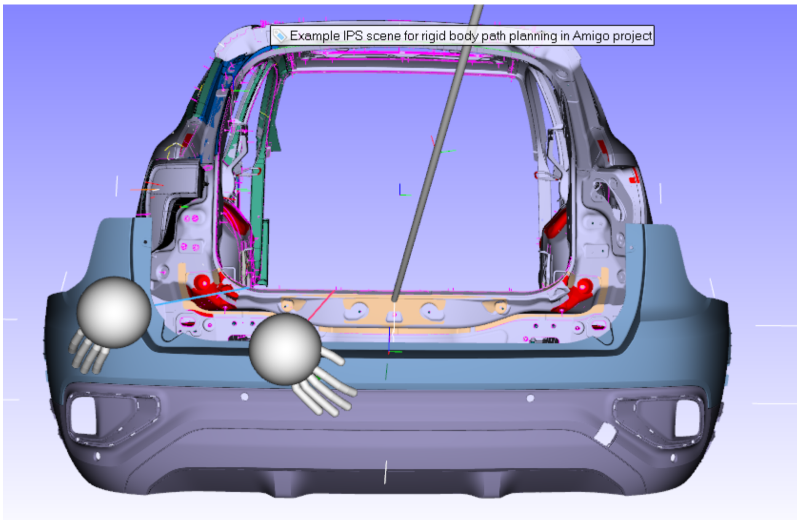

Figure 4.9: Screenshot of the hand position and vision point for the first manual simulation of the bumper.

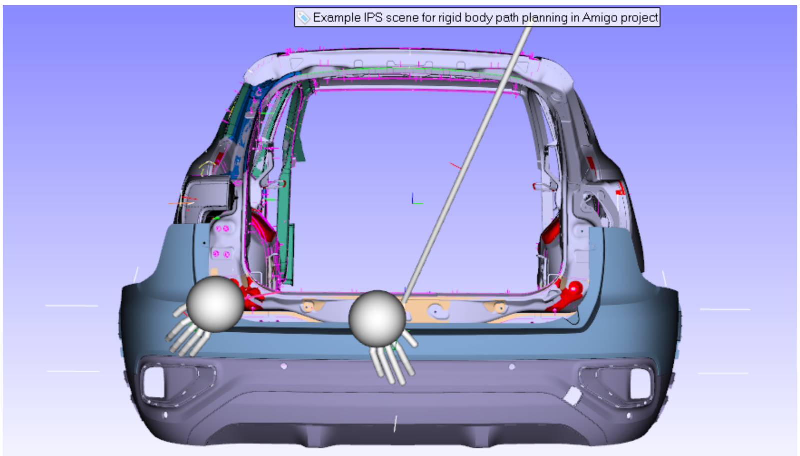

Figure 4.10: Screenshot of the hand position and vision point for the second manual simulation of the bumper.

In Table 4.5, the result of the simulations is presented. If the simulation result is different in comparison to the manual assessment in Table 3.2, the cells are colored red. When comparing the manual assessment and the automatic simulation for the bumper, it is only criteria one and six that are the same for all the runs. Criterion five was the opposite for all the automatic simulations except for one. In the comparison between the manual assessment and the manual simulation, it is criteria one and five that are the same. Criteria three, seven, nine, and eleven are the opposite for both the manual and automatic simulation. The result of the comparison between the simulation and the manual assessment for the bumper is therefore that two to three out of seven criteria are the same as the manual assessment.

Table 4.5: The complexity criteria for the automatic and manual simulation of the bumper. If the simulation differs from the manual assessment the cell is colored red.

Simulation	Grip	HC 1	HC 3	HC 5	HC 6	HC 7	HC 9	HC 11
Automatic	Right	No	Yes	No	Yes	Yes	Yes	No
		No	Yes	Yes	Yes	Yes	Yes	No
	Left	No	Yes	Yes	Yes	Yes	Yes	No
		No	Yes	Yes	Yes	Yes	Yes	No
	Both	No	Yes	Yes	Yes	Yes	Yes	No
		No	Yes	Yes	Yes	Yes	Yes	No
Manual	Both	No	Yes	No	No	Yes	Yes	No
		No	Yes	No	No	Yes	Yes	No
Manual assessment		No	No	No	Yes	No	No	Yes

4.3 Improvements

In this section potential improvements from observations during the validation and suggestions from the interviews are described.

4.3.1 Potential Improvements from the Validation

Potential areas of improvement have been observed while performing the validation with the combined program. The first observation is the potential of saving a specific assembly complexity analysis in RD&T. If the result from the analysis window is closed, the same analysis cannot be reached again, and if run once more, the automatic simulation will produce a different grip. The second observation is an issue in the panel when settings for the assembly complexity analysis are decided. If the decision of which hand to use is made before choosing assembly direction and vision point, the program automatically sets it to the left hand. The third observation is that in RD&T, the article to assemble is selected as planning geometry and therefore not viewed as a collision geometry. This allows the manikin to go through the planning geometry and create unrealistic simulations. The fourth observation is that the same assembly situation can create multiple different results depending on what grip and vision are selected, affecting the assessment of how to move further with an issue. The last observation is that the ergonomic evaluation is based on RULA, hence focusing on the upper limbs. To include the ergonomics of the whole manikin's body, REBA could be included in the evaluation of the criterion.

4.3.2 Potential Improvements from the Interviews

In this section, the result of the questions specifically about the new combined program is presented. More specific questions were asked to people working with RD&T or IPS IMMA. The designers and PQ were asked about the purpose and overall functions of the combined program. None of the interviewees had worked with the program prior to their interview as presented in Figure 4.2 in Section 4.1.1. One from geometry and one from manufacturing had previously seen demos and had therefore a clearer view of the functions compared to the rest of the interviewees. In the interviews, several improvements and potential functions were mentioned. In Table 4.6, the result is presented about potential areas of continued development. It was two interviewees contributing with answers, one from geometry and one designer. In Table 4.7, potential functions the interviewees were interested in having if using the software are described. Potential functions were described by eight people from the groups geometry, designers, and manufacturing. Compared to Table 4.6, this is based on the explanation of the program, without testing it.

Table 4.6: Potential areas of development suggested from the interviewees.

Second order codes	Mentioned by
The answers are digital and do not provide answers on how or what is bad	G
Static simulation with only one view and one grip	G
The grip of the manikin is unclear	G
Complexity within the system is not included	G
Few people who know RD&T	D

Table 4.7: Potential functions suggested from the interviewees.

Second order codes	Mentioned by
Tolerances in IPS IMMA instead of a nominal environment	G M
Send the files between RD&T and IPS IMMA	G M
The result explaining why it is bad or good	G M
The result being a variance factor instead of a number between 0 to 1	G
Manufacturing feasibility score	G
Fixture equipment	G
Connection between CATIA and IPS IMMA	D
How bad or good is the result	D
The effect of material with the assembly complexity	D

An improvement mentioned in both Table 4.6 and Table 4.7 is the result of the simulation. As described in Section 2.4, the result of the program is a combined number between the stability analysis and the assembly complexity, between zero and one. It is described by G1, that this number feels too digital to work with and apply in reality. To be able to apply the tool it is important to know why it was bad, how it was bad, and what needs to change. In Table 4.7, the importance of knowing how or why the result is bad or good is also expressed. D1 described that it is important to know if it is 10 % or 90 % bad. G2 suggested another way to present the result, where instead of receiving a number between zero to one, the result could be an additional variance. This variance could then be added to the regular calculated variance, to include the effects of manual assembly complexity.

The process of IPS IMMA can be used automatically or by manually choosing grip. G1, mentioned some experienced issues when watching a demo of the program. One of them is the static grip and view point of the manikin, compared to how an operator would operate in reality when assembling a part. The grip plays a significant role in determining how the manikin moves and therefore it affects the result. It was commented that it was confusing how the grip works, and how the automatic simulation proposed weird grip positions. In the environment of IPS IMMA, the models of the products being assembled are based on nominal models. In the interviews, G3 and M2, talked about being interested in having the possibility to have models with variations in the IPS IMMA software. That means that the result of the variation simulation from RD&T would be included in the model during the feasibility of assembly simulations. G2 and M1 expressed interest in the opportunity that this program could make it possible to send RD&T files and IPS IMMA files between geometry and manufacturing more efficiently and use each other's results.

Another area of improvement that was mentioned is the program's lack of ability to simulate complexity within a system. G1 described that sometimes it is the assembly of multiple articles that creates the complexity and not only the assembly of one article on the car, as to how the program currently works. The last code in Table 4.6, is that only a few people know RD&T, and it is also connected to how D2 would be interested in a connection between CATIA and IPS IMMA too. Other potential functions mentioned were a manufacturing feasibility score, adding fixture equipment into the simulation, and including the effect that materials can have on the assembly complexity if they are sensitive or easily harmed.

4.4 Current Work Process

In this section, the interview results related to the work process at CEVT are presented. The section provides information regarding gates, meetings, input, communication, responsibility and potential applications.

4.4.1 Gates

The work process for the product realization at the company consists of different work phases that end with a gate. When a specific gate is reached, there are certain requirements that shall be fulfilled at that deadline and there is a release of what has been done so far. The further the project matures through the different phases and gates, the smaller changes are allowed. The gates mentioned as important during the interviews are presented in Figure 4.11. The three different timelines in the figure are proceeding simultaneously. On the timelines for styling and mechanical development, each phase starts after the previous gate has ended.

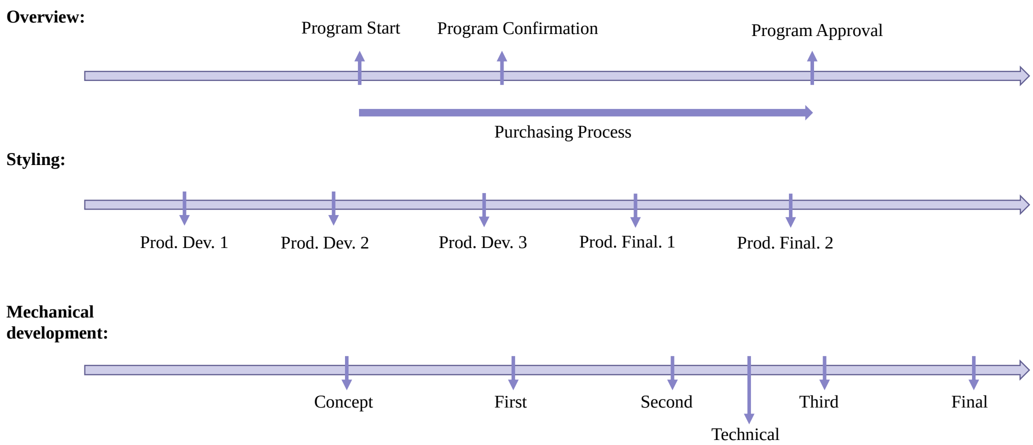

Figure 4.11: The gates mentioned as important in the interviews.

There are three milestones creating an overview of the project, in the first timeline, where the budget and funding are approved in different steps. The first is *program start*, which is the milestone where the project starts, and the budget is approved until the second milestone *program confirmation*. The second milestone is the program confirmation, where the funding until the third milestone *program approval* is approved and confirmation regarding the business balance is made. The third program milestone is the program approval, where the project is mature enough to start tooling. The *purchasing process* is the process where the designers make purchase requests of articles to the suppliers. The purchasing process starts at the program start and lasts until the program approval. The purchasing process lasts for a longer time period since different parts have different lead times.

The second timeline describes the shows the product realization process for the styling department. Styling is the department responsible for ensuring that the vehicle has an attractive appearance for the customers. The styling department has its own gates showing the maturity of a project as it progresses. Firstly, they have three *product design development* gates (Prod. Dev. 1-3 in Figure 4.11), which are followed by two *product design finalization* gates (Prod. Final 1-2 in Figure 4.11), where split-lines are included for the first time. Split-lines can be explained as the distances and relations between the components within the product. In between the two product design finalization gates, only smaller changes are allowed.

The third timeline in Figure 4.11 shows the product realization process for mechanical development. After each gate in the mechanical development, there is a design verification during a few weeks to review what has been done in the previous phase. Before the gate *concept*, a concept is chosen among the alternatives that are investigated. Not every attribute is included in the development yet, and placeholders are used for some parts. At the concept gate, geometry shall have a Geometric Design and Tolerancing (GD&T) with defined locators and tolerances for the concept that is being evaluated. There should also be a concept for the assembly and a reference positioning system.

At the gate *first* in the mechanical development timeline, the full concept is found and every attribute is now involved. Geometry shall have the first version of the GD&T done and the first edition of the CATIA models for the different parts shall be finished by the designers. The dimensional target strategy should be included in the process. Furthermore, holes and surfaces should be included in the modeling of the parts. During the period between the first gate and the third gate the GD&T shall be confirmed by other concerned attributes and the suppliers.

At the gate *second*, they should be prepared for the *technical* gate that occurs during the following phase. The technical gate does not follow a specific phase on its own and is more of a deadline. The technical gate entails the deadline for the last technical input that can be given before styling makes its product design finalization 1 and includes the set-up of the nominal gaps. At the second gate, all parts should be assembled correctly and the strategy of the positioning system should be correct. No new parts are allowed, as the welding is locked.

At the gate *third*, which occurs soon after program approval, it is time to start tooling, which means that changes can be expensive. In addition, all the drawings shall be finished. The positioning system is released five days after the gate is released. After the third gate, it is no longer allowed to change the thickness of the material, or the strength of the material and the designed parts should fulfill the requirements and thereby be locked. During the last phase before the gate *final*, only small adjustments are allowed. Finally, after the final gate, no more changes should be made. The latest version of the GD&T should be included, and it should match the release at the gate product design finalization 2.

4.4.2 Meetings

During the interviews there were three meetings mentioned that deal with geometry and/or manual assembly complexity related topics. These are: the synchronization meeting, the Vehicle Integration Meeting (VIM) and the engineering meeting. The synchronization meetings are led by the engineers at geometry and aim to solve issues regarding the geometry. Which people participate in the synchronization meeting depends on the issue that needs to be discussed. However, the participants from geometry and the designer who has designed a part in the affected region are always included. PQ and people from manufacturing feasibility may also participate. The VIM is convened by concept engineers at the manufacturing feasibility department. Thereby, they have not the same role as the manufacturing group that are interviewed. The VIM aims to balance the attributes and thereby find a concept on which everyone can agree. Meanwhile, the VIM meeting provides an overview of how several components work together and includes different designers. The engineering meeting is summoned by the designer to discuss the parts that they are designing. The meeting is cross-functional and includes different attributes, such as geometry, manufacturing feasibility, PQ and others.

4.4.3 Input

During the interviews, it was asked about what input is needed for each interviewee's result and who is the receiver of their results. These answers were mapped and are presented in Figure 4.12. The figure only includes the groups represented during the interviews. The designers deliver their designs and thereby give information to both manufacturing, PQ, and geometry. After receiving the designs, manufacturing judges the CAD file of the designs to find whether they are feasible to assemble and reports back. Geometry makes calculations on the information from design and delivers their GD&T back to the designers. Meanwhile, PQ delivers the product requirements to the designers. Furthermore, PQ also delivers their requirements to geometry who delivers their calculations back. There were no deliveries mentioned between PQ and manufacturing or geometry and manufacturing when the interviewees were asked about the input needed or the receiver of their results.

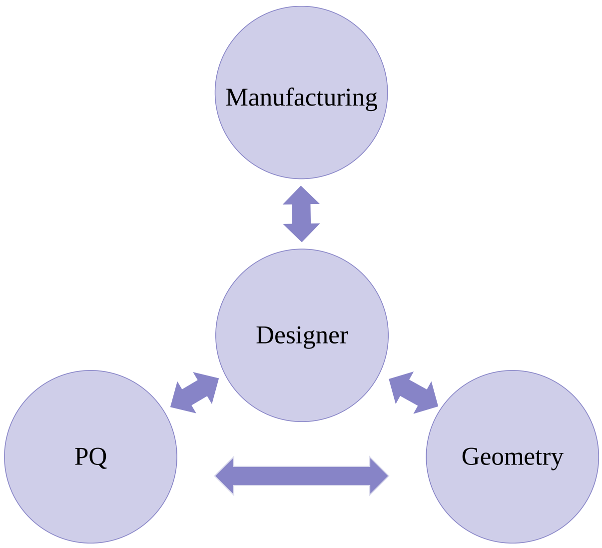

Figure 4.12: A map of how the delivery and feedback went between the interviewed groups.

4.4.4 Communication

The interviewees were asked questions regarding communication and the result is shown in the Tables 4.8 to 4.13. Note that the same interviewee may have expressed multiple codes, even codes that are contradicting each other since the interviewee might have reasoned from different perspectives.

Table 4.8 displays the answers to the question "How is the communication with the people working with IPS IMMA/ergonomics?" and in some cases follow-up questions. The codes foremost relate to the perception of current communication with the people working with IPS IMMA/ergonomics. This question was asked to the groups geometry, designers, and PQ.

The most common answer regarding the communication with the people working with IPS IMMA/ergonomics from geometry was that the current communication is minimal. The reason why some geometry employees have more communication appears to be because of their own initiative. In addition, it was mentioned that it can be difficult to find the perfect level of communication. It was also said that the levels of communication with the people working with IPS IMMA/ergonomics differed within geometry, depending on the employee.

Furthermore, the designers were asked about the communication with the people working with IPS IMMA/ergonomics. It is stated that communication foremost takes place when needed. However, there is no clear process for how the communication should take place. The designers do not currently receive any feedback about ergonomics from the production plant in China, which could have been appreciated. The group PQ stated that communication with IPS IMMA or assembly ergonomics is not a part of their role, as they are separate attributes.

Table 4.8: The codes based on the answers to the question "How is the communication with the people working with IPS IMMA/ergonomics?"

Group	Second order codes	No. of mentions
Geometry	Minimal communication	4
	Have communication on own initiative	2
	Difficult to find the right level of communication	1
	Level of communication varies within our group	1
Designers	Communication when needed	1
	No clear process for communication	1
	Would like ergonomic input from the production plant in China	1
PQ	No communication with IPS IMMA or assembly ergonomics	1

In Table 4.9 the answers to the question “What would you think about an extended collaboration?” are displayed. The majority of geometry expressed a positive attitude towards increasing the communication with the people working with IPS IMMA. Furthermore, a potentially negative aspect of increased communication mentioned was the risk that more people involved in a process might increase the complexity and make the process slower. One interviewee from geometry expressed that it might be beneficial for the designers responsible for specific articles to increase their communication instead, with the people working with IPS IMMA instead of geometry. Furthermore, it was suggested that geometry could be leading, as they work cross-functionally across factories. However, a drawback of geometry leading could be that it would be time-consuming and therefore probably would not work. It was also mentioned that it is difficult to find the right level of communication.

In addition, the designers in Table 4.9 were asked about a similar increase. One of the interviewees expressed interest in looking at things in a similar program, based on CATIA instead, which is a program that they frequently use. One of the designers expressed both a positive and a negative attitude towards increased communication, as “all communication is good”. However the designer is negative towards having more meetings only to have more meetings and states that it needs to be well integrated into the work process.

Table 4.9: The codes based on the answers to the question “What would you think about an extended collaboration?”

Group	Second order codes	No. of mentions
Geometry	Positive attitude towards an increased communication	4
	Negative attitude towards an increased communication, because of complexity	1
	Positive attitude towards the component owners having increased communication	1
	Geometry can be cross functional	1
	Difficult to find the right level of communication	1
Designers	Positive attitude towards doing things in own program	1
	Positive attitude towards increased communication	1
	Negative attitude towards adding unnecessary meeting	1

Table 4.10 displays the answer to the question “How is the communication with the people working with RD&T?” and in some cases follow-up questions. The interviewees from the group manufacturing agreed that they have communication with people working with RD&T in order to judge concepts and assess problems and they also meet at the VIM meetings. Regarding their attitudes about increased communication one of them has a positive attitude and the other one is uncertain, because they are not sure who works with RD&T. One of the interviewees from manufacturing is open to an extended collaboration by enabling different softwares, such as RD&T and IPS IMMA, to speak to each other and the possibility to use each other’s results. Furthermore, the designers agree that they have good communication with the people working with RD&T. The frequency of the communication may depend on the interpersonal chemistry between the designer and the person working with RD&T. The group PQ said that they have good communication with the people working with RD&T.

Table 4.10: The codes based on the answers to the question “How is the communication with the people working with RD&T?” with follow-up questions.

Group	**Second order codes**	**No. of mentions**
Manufacturing	Communication to assess problems	2
	Communication at VIM	1
	Positive attitude towards increased communication	1
	Uncertain about increased communication	1
	Open to collaboration by using each other’s results	1
Designers	Good communication	2
	Depends on interpersonal chemistry with the person who works with RD&T	1
PQ	Good communication	1

Table 4.11 displays the answers to the question “How is the communication with the designers?” and “Do you have the possibility to affect the design of parts?” with follow-up questions that were asked to the manufacturing group. Manufacturing said that they have contact with the designers during the weekly VIM meetings and on their own initiative when a problem arises. Furthermore, they said that it is easier to change the product earlier in the work process. One of them said that they have sufficient communication and do not need more. It was also said that they have the possibility to affect the design of the product if it does not fulfill the assembly requirements.

Table 4.11: The codes based on the answers to the question "How is the communication with the designers?" and "Do you have the possibility to affect the design of parts?" with follow-up questions.

Group	Second order codes	No. of mentions
Manufacturing	Weekly meetings and contact on initiatives	2
	Easier to affect the product earlier in the design phases	2
	Sufficient communication with designers	1
	Possibility to affect the design if assembly requirements are not fulfilled	1

Table 4.12 displays the answers to the asked questions regarding feedback. That includes "What do you think about the feedback that you get?" with follow-up questions that were asked to the designers and "How is your process for giving and receiving feedback?" that was asked to PQ. One of the designers states that the feedback is good. Both from all the attributes after a release and also daily feedback in certain periods from some attributes. The other designer includes the manufacturing feasibility in meetings to receive feedback. It is also stated that early feedback is beneficial. The group PQ said that feedback is given through e-mail and deliveries.

Table 4.12: The codes based on the answers to the questions regarding feedback. The designers were asked: "What do you think about the feedback that you get?" with follow-up questions and PQ was asked "How is your process for giving and receiving feedback?".

Group	Second order codes	No. of mentions
Designers	Good feedback both after releases and daily in certain periods	1
	Includes the manufacturing feasibility department in meetings	1
	Beneficial with early feedback	1
PQ	Feedback is given through e-mails and deliveries	1

Table 4.13 displays the answers to the question "After you have done the final delivery of a design/construction and it has moved to industrialization, are you still involved in changes?" with follow-up questions. This question was only asked to the designers. The designers stated that they receive feedback regarding assembly ergonomics early in the process. Furthermore, when a product is industrialized it is too late for completely new solutions, but they are still involved until all of the problems are solved.

Table 4.13: The codes based on the answers to the question "After you have done the final delivery of a design/construction and it has moved to industrialization, are you still involved in changes?" with follow-up questions.

Group	**Second order codes**	**No. of mentions**
Designers	We receive feedback regarding assembly rather early in the process	1
	Involved in changes until problems are solved	1
	Too late for new solutions after industrialization	1

4.4.5 Responsibility

In the interviews, the interviewees were asked if they would be interested in including the software in their work. In Figure 4.13, the result of this question is presented. It is divided into yes, no, or uncertain and which group the interviewees are part of. In the result, five people were interested, three said no, and three were uncertain. When developing their answers, it was expressed by three people that time was an important factor when considering potentially including the program in the work process. Specifically, the interviewees thought it was important to have enough work time to use the program, that using the program saves time in the product realization process or that the software is smooth and quick to use.

In the interviews, it was examined who should perform the analysis of the program and who should be responsible for the result. In Figure 4.14, the answers are divided between geometry, manufacturing, a collaboration between geometry and manufacturing, and uncertain. Zero people answered geometry, three people answered manufacturing, three people answered a collaboration and two people were uncertain. In the answers, manufacturing prefers a collaboration, and geometry answers more towards that it is manufacturing's responsibility. D1 suggested that it could be interesting with someone in each designer department with RD&T knowledge, who could run a quick analysis to provide fast information about the assembly complexity for the different articles.

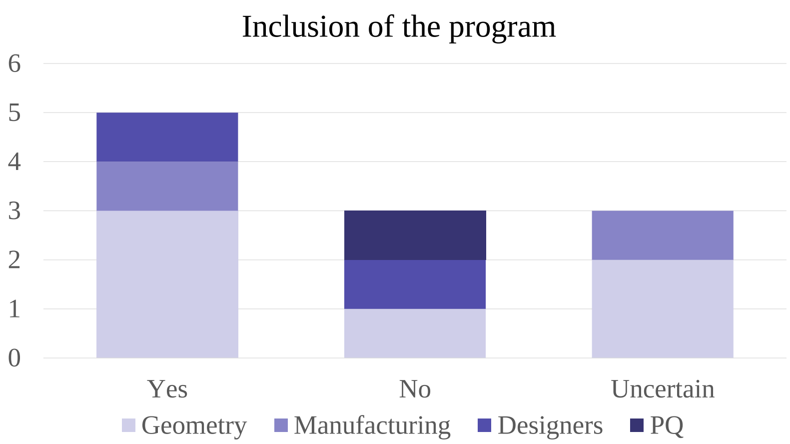

Figure 4.13: A bar chart over the interested of including the combined program in the daily work.

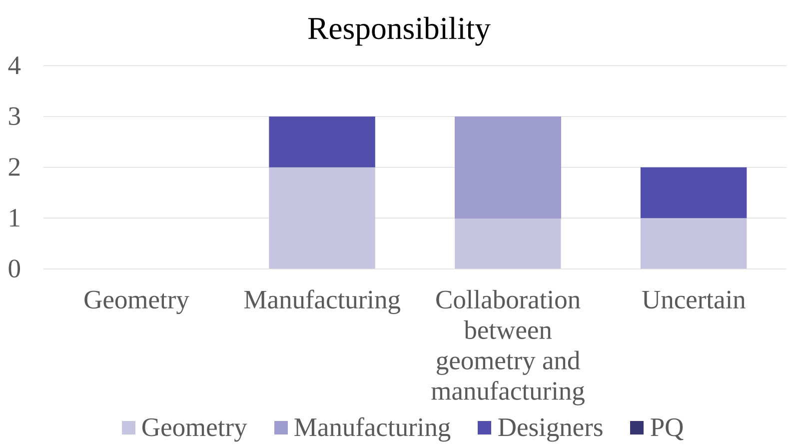

Figure 4.14: Bar chart over who should be responsible for the combined program.

4.4.6 Potential Applications

In the interviews, benefits, reflections and potential use in current work were discussed. In Table 4.14, the answers from the interviews are organized into what the interviews mentioned as important aspect for a potential application of the combined program. Mentioned by three people were the importance of the program being simple, smooth and user-friendly. The broad themes otherwise were that it could generate additional information and a deeper perspective of how feasibility of assembly is seen. With this additional information, the discussion regarding the connection between geometry and manual assembly can be supported with an assessment instead of a gut feeling. Another benefit was that the program could make the communication between geometry and manufacturing easier and more efficient if the program and the complexity criteria work as a link. P1 thought the requirements on the product could be affected both positively and negatively by the use of the combined program, because the program can potentially lead to a change in the design.

Table 4.14: Table with codes about potential application of the combined program.

Second order codes	Mentioned by
Simple, smooth and user-friendly	G G M
Fact to support one's ideas	G G D
Additional information	G G
Broader perspective on feasibility of assembly	G D
Easier communication between geometry and manufacturing	M M
Potentially effect the requirements	P

From G1, it was brought up that the program may not be interesting for every article, and G6 expressed that it can be beneficial in the more difficult discussion about the articles. Moreover, G5 describes that it would be interesting to be able to run a quick analysis for every part, to see if something has been missed. G4 discussed the importance of everyone affected by the program needs to be interested in using it.

Uncertainties and questions about how the program works and would affect the current work was raised. From G2, the question was raised whether something about how RD&T is operated and used today needs to change. G2 also raised the question if knowledge about both programs is required to use the new combined version. The question of what the input from RD&T to IPS IMMA is, was asked from G4 and what the new benefits were compared to using CAD files in IPS IMMA. G1 mentioned that deciding who should conduct the analysis and how the process should function could be difficult. Furthermore, G1 also mentioned that it might be hard to determine when a result from the program is considered to be bad.

4.5 Summary of the Result

In the following list, there are some takeaway messages from the different sections in the result chapter.

- In the Section 4.1.1, **interviewees knowledge about the program** it was introduced that five out of eleven interviewees had previously heard about the AMIGO project. Six interviewees had worked with RD&T and two interviewees had worked with IPS IMMA before. Furthermore, two interviewees had seen a demo of the combined program.
- In the Section 4.1.2, **manual assembly complexity**, it was shown that most of the interviewees had their own definition of manual assembly complexity and the majority considered it in their work. Fewer interviewees, although still a majority, considered the definition of manual assembly complexity that was used in this master thesis in work. Furthermore, a clear majority of the

interviewees thought there is a connection between assembly ergonomics and the geometrical quality of the product.

- In the Section 4.2, **validation**, the simulation result from the combined program RD&T/IPS IMMA were compared to the manual assessment. In total, eight runs were performed for both the rear lamp and the bumper. The result for the rear lamp was that four to five criteria were the same as the manual assessment of the rear lamp. For the bumper, two to three criteria were the same as the manual assessment of the bumper.
- In the Section 4.3, **improvements**, potential improvements from observations from the validation and from the interviews was presented. Examples of these were to present the result as a variance, knowledge on how to work with the result, and be able to send files between RD&T and IPS IMMA.
- In the Section 4.4.1, **gates**, it is worth to be noted that there are different gates, that can be considered deadlines in the work process. As the work process progresses the project becomes more mature and fewer changes are allowed. Important gates for the mechanical development were concept, first, second, third, technical, and final. After each gate in the mechanical development, there is a design verification to review what has been done so far.
- In the Section 4.4.2, **meetings**, three meetings deal with geometry and/or manual assembly complexity-related topics. These are the synchronization meeting by geometry, the VIM by concept engineers, and the engineering meeting by the designers.
- In the Section 4.4.3, **input**, the delivery flows are mapped between all of the groups of interviewees. There are deliveries and feedback between all the groups except for PQ and manufacturing and manufacturing and geometry.
- Some takeaway messages in the Section 4.4.4, **communication** is that the majority of geometry states that they have minimal contact with the people working with IPS IMMA. However, they have a positive attitude toward having increased communication. Furthermore, designers communicate with the people working with IPS IMMA when needed, while PQ does not have any communication with them. Regarding the communication with the people working with RD&T, manufacturing states that they communicate to assess problems and at VIM, while the designers and PQ state to have good communication with them.
- In the Section 4.4.5, **responsibility**, the interviewees were asked if they were interested in including the program in their work. Five people answered yes, three people answered no, and three were uncertain. It was also discussed who should be responsible and performing the analysis. Zero people answered geometry, three answered manufacturing, three answered a collaboration between geometry and manufacturing, and two people were uncertain.
- In the Section 4.4.6, **potential applications**, different reflections were raised by the interviewees about the program. Aspects such as benefits, potential applications, and questions about the program were covered.

5
Suggested Implementation in Work Process

The following section proposes how the combined program RD&T/IPS IMMA shall be implemented in the work process at CEVT. The suggestions assume that the program is validated and functions as planned. The result is based on answers received in the interviews and discussions with the company supervisor. In order to include the program in a work process, there are certain issues identified that need to be considered, which are presented in the following list. Thereafter, the following sections present suggestions on how to handle the issues. One section can contain more than one suggestion.

- Who should be responsible for this program? See 5.1.
- Who should use/make the manual assembly complexity analysis with this program? See 5.1.
- If multiple departments are involved, how shall the communication occur? See 5.2.
- How should the result of the program be used during daily work? See 5.3.
- When in the work process should the analysis be conducted? See 5.4.
- How should the changes be accepted by the employees? See 5.5.

5.1 Responsibility and Use

Previously in the result, the interviewees' opinions regarding who should be responsible for the analysis made in the program were presented in Figure 4.14. The result showed a tied result between having a collaboration and that manufacturing feasibility are responsible. Firstly, a collaboration between geometry and manufacturing feasibility is suggested. That is, because manufacturing feasibility has the overall responsibility to ensure that the vehicle can be assembled and that there is beneficial ergonomics for the operator. Meanwhile, the combined program is based on RD&T, which is used by geometry and not manufacturing feasibility. Thus, they have the knowledge on how to use it. Therefore, it is suggested that geometry should implement the analysis. In conclusion, it is firstly suggested that the responsibility is shared between geometry and manufacturing feasibility, where geometry is responsible for conducting the analysis by the program.

The role responsible for including the input from different attributes is the designer constructing the part. Therefore, the second suggestion, in accordance with the idea by an interviewee in Section 4.4.5, is that an employee with RD&T knowledge can be responsible for conducting the analysis at each design department, as a support function. That could either be an employee from geometry or a designer who belongs to that specific department. Meanwhile, manufacturing feasibility is primarily responsible for the ergonomics, meaning that the responsibility in this case would be a collaboration between a designer or an employee at geometry, and manufacturing feasibility.

5.2 Communication

In Section 5.1 a collaboration between manufacturing feasibility and geometry was suggested. In Table 4.8 it is shown that the majority of geometry perceive that they have minimal communication with the people working with IPS IMMA/ergonomics. Meanwhile, they have a positive attitude towards increasing communication, which is shown in Table 4.9. In Table 4.10, manufacturing mentioned that they have communication with “the people working with RD&T”, to assess problems and at the meeting VIM. One interviewee was positive and one was uncertain regarding an increased communication. Based on this, a majority appears to be open for an increased collaboration. The collaboration should work in a structured manner, to ensure that everyone knows what their responsibilities are and when in the work process it shall be performed. Performing an analysis could be considered a delivery of result that shall be performed at a specific time in the work process. Regarding the second suggestion, where the analysis would be performed by a support function at the design department, it is currently assumed that the communication in the department works and can therefore be easier to implement this suggestion. During the interviews the questions were also focused on the communication between different departments. In case of an implementation of this option, it would be beneficial to look further into how the communication works within the department. It was also described that the manufacturing feasibility department works with design to pursue assembly feasibility issues, thereby a communication path already exists.

The feedback that comes from the analysis by the program should be discussed in a defined meeting, to ensure that it happens in a structured way. Which meeting should depend on which department is conducting the analysis, geometry or a support function at the design department, which was suggested in Section 5.1. In case the geometry department conducts the analysis, the synchronization meeting could be a beneficial choice for the same reason. Additionally, if the design departments are responsible, the engineering meeting might be a favorable choice, since the designers are responsible for the meeting. However, it is important that the manufacturing feasibility department is included in whichever meeting is chosen as they have the ultimate responsibility for assembly ergonomics.

5.3 Potential Use of the Result

As previously described in Section 2.4, the result of an analysis in this program is a list of complexity criteria, that are either high or low. Furthermore, there is a SUM (RMS) value that includes both robustness and assembly complexity. These results would be possible to use in different manners. The list of the complexity criteria could be used to highlight potential problem areas that need improvement. Furthermore, the SUM (RMS) value could be used to decide whether a component needs to be further improved in regards to manual assembly complexity. The SUM (RMS) could also be used to compare different product concepts. The following list gives different suggestions for how the results can be used by the departments.

- Geometry can send the result of the complexity criteria to manufacturing feasibility who can pursue the criteria of high complexity with the designers.
- If one person at every designer department would know RD&T and be responsible for implementing the analysis, the feedback from the complexity criteria could come directly to the designers. Then a decision can be made whether manufacturing feasibility shall be alerted regarding a specific part or not.
- The SUM (RMS) value of the program can be used as a manner to decide whether manufacturing feasibility would need to review the part.
- In case of a choice between more than one solutions, the SUM (RMS) value could be used to choose the option less affected by manual assembly complexity.

5.4 Time in Work Process

The gates in the work process are described in 4.4.1. To be able to make the required changes early in the process, when it is cheaper, the analysis should be performed at an early stage. Meanwhile, the process should be mature enough to ensure that the analysis is performed on the final position for the part. It is therefore suggested that it should be performed by the first gate, so that it is done for the technical gate. It would also be possible to include the analysis in the design verification after the different mechanical development gates, starting at the second gate, to ensure some maturity. Thereby, the analysis would be conducted at the design verifications after the second and the third gate. It is important that the people working with the combined program have sufficient time in their schedule to be able to perform the analysis. The analysis should also therefore be user-friendly and simple to use, which is desired by potential users in Section 4.4.6.

5.5 Acceptance

In Section 5.1 it is suggested that geometry may take part of the responsibility of conducting the analysis in the work process. Even though it was found in Section 4.4.5 that the employees at geometry tend to think that manufacturing alone should be responsible for the analysis. Therefore, it would be important that they agree with taking or sharing the responsibility.

In order to implement the use of the combined program in a beneficial manner, change management can be a useful tool. The Section 2.7 presents two models for change management, with certain common elements. The models agree that there should be a vision of what the change shall entail, both regarding objectives and strategy. The objective from the implementation of the RD&T/IPS IMMA could be that less mistakes from operators shall negatively affect the geometrical quality. In Figure 4.6, it was shown that a clear majority thinks that there is a connection between ergonomics and geometry. In case geometry becomes responsible for conducting the analysis, it can therefore be argued as part of the vision that geometry shall share responsibility for all aspects affecting the geometry.

In both models it is also mentioned that the change must be supported by employees with different kinds of power in the organization. When choosing which employees should have more responsibility regarding this kind of analysis, it should be considered who is interested in performing it. That is to ensure that the first people working with it become a part of the guiding coalition or key-players who will inspire others until it becomes part of company culture.

6 Discussion

In this section, the result from the validation, the improvements, and the suggested implementations in the work process is discussed.

6.1 Validation

The validation method of the simulation program became simple in comparison to the validation theory described in Section 2.5, describing different methods such as event validity and the Turing test. The aim was to perform one of these methods for the validation but was limited by the minimal amount of data available to compare with, to fully validate the program. Instead, a smaller validation was performed for one case, testing the different grips and the automatic and manual functions. The Turing test, where a professional tries to tell which result is from a simulation and manual assessment was potentially intended but was not performed when concluding that the simulation's assessment was not sufficiently refined. The manual assessment was assessed to be correct, based on reviewing and having access to the same material as when the original assessment was performed. The people performing the assessment were knowledgeable about the complexity criteria and the specific manual assembly operation at the company. In the manual assessment, it is also commented on why a criterion is considered to be an HC criterion, to allow the reader to consider its credibility.

The validation for the rear lamp and bumper faced some issues. When the simulations for the validation were run, not all of them were successful. One of the problems was errors with the grip, where the manikin could not perform the suggested grip by the automatic function. Therefore, the simulation needed to be run until a successful run was achieved by making adjustments. Adjustments were done by changing the start position for the article, by moving it further away. For the rear lamp and the bumper, all the planned runs were possible to implement. In the result, only the successful runs were presented, excluding the runs with errors where the program crashed or grip error. The bumper required multiple runs when using both hands for the automatic, there the size of the article made it difficult to find an optimal grip position which was successful. The program is limited to assembling only one item from a starting position to a final position. Therefore steps e.g., fastening screws or clips, are not included in the simulation, making the simulation simpler than how the assembly is performed in real life. In the video clips from the production in China over the assembly of the bumper, it is also two people assembling the article, which is not possible in the simulation program and therefore adjusted to only one manikin performing the assembling. For the rear lamp, assumptions had to be made, because no available video clips for how the assembly process was performed.

One of the most extensive sources of error in the validation was the tuning of the complexity criteria. In Section 2.4, the assessment of the criteria in the software is described. These definitions determine if a criterion is high or low and have a noticeable effect on the result. Because of this, HC criterion one *many different ways of doing the task* and HC criterion nine *operations must be done in a certain order/sequence*, always replies no respectively yes in the result regardless of the assembly simulation. Out of these two criteria, the only HC criterion in the manual assessment was for the rear lamp for criterion nine, when fastening the lamp in the luggage, because this is not performed in the simulation, the criterion should have been considered an LC.

For the rear lamp and the bumper, HC criterion three *time demanding operations*, was simulated as yes for all runs. For the manual assessment, both parts were assessed as no. For achieving LC in the simulation, the time needed to be under 105 TMU. This criterion focuses on the assembly time for the part, but when deciding the starting position, the part needed to have a certain measure away from the assembly position for the simulation to function. This was experienced especially for the rear lamp, where the program stopped working until the part was successively moved out. Missing from this criterion in the program is that the time limit should depend on the highest assembly time operations, and therefore differ. The set time is based on a study for a car assembly, which does apply in this validation, but the result is potentially affected by the problem with the start position or the time to assemble the part.

Out of all of the seven criteria that the simulation program evaluated, the HC criterion five *poor accessibility* and HC criterion six *hidden operations* were the only criteria with some variance, even if both tended to be yes. From the manual assessment, criterion five for the rear lamp was a potential HC criterion because of the fastening of the lamp from inside the luggage. Like criterion nine, this criterion should therefore have provided a no in the assessment. This criterion is judged based on an 8 cm sphere around the wrist of the manikin and if it is a collision with the obstacle geometry it is HC. Because the rear lamp is assembled into the body in white and is not a large article compared to the bumper, the sphere easily can come in contact and therefore provide HC. Hence, there is mostly HC for criterion five, for both the rear lamp and the bumper, especially with the automatic where the hands were placed both on the outside and inside of the parts.

The same discussion can be held for criterion six as for criterion five. For criterion six to be considered as HC, the vision line between the manikin's eyes and a decided point needed to be broken by the collision geometry. The manual assessment for criterion six is LC for the rear lamp and HC for the bumper because of hidden clips. As in the case of criterion five, securing the hidden clips is not included in the simulation and therefore the simulation should judge criterion six as LC for both parts. The vision part in the automatic simulations is placed at the same point in every simulation automatically. For the rear lamp, it is on the top, and for the bumper, it is on the right side. Because the automatic simulation put the vision point inside and on the edge of both parts, the vision line was easily colliding with the collision geometry and therefore the criterion was HC for all the automatic runs. It was only for the manual simulations, LC was achieved, when the vision point was manually chosen to be on the top and surface of the parts, which gave easier access to it. Still, one of the rear lamps' manual simulations was considered HC.

For HC criterion seven *poor ergonomics conditions*, the result of the simulation was HC for both parts. In the manual assessment, it was considered HC for the rear lamp because of a bent/twisted position when assembling the lamp in the luggage and LC for the bumper. As described earlier, the manikin does not perform the part of assembling the lamp in the luggage, and therefore the simulation should provide LC for both the rear lamp and the bumper. In the simulation, criterion seven is HC when the ergonomic evaluation method RULA is zero, the answer is therefore always HC because RULA is graded between one to seven and therefore does not provide any valuable input about the assembly complexity. Since the assembly operations include movements of the full body it could be beneficial to also consider the REBA assessment while evaluating the criterion. This can be done by either basing the result of criterion seven on REBA or basing it on both ergonomic evaluations, whichever provides the least beneficial result. That is, to ensure that potential ergonomic risks are discovered through using this program.

The last criterion the simulation judges is HC criterion eleven *accuracy/precision demanding task*. As described in Section 2.4, this criterion consists of two parts, precision, and demanding task, where the simulation only considers the demanding part, by judging if the start position is 5 m from the final position. In the manual assessment, the bumper was assessed to be HC, and the rear lamp to be LC. The simulation result was provided with LC for all runs, for both articles, because the articles' start position was positioned closer than 5 m. As described in 3.2.1.1, the starting position was put as close as possible to only simulate the assembly operation. Data for where the original position in production was not available and from the available video clip of the assembly of the bumper, the starting position is not shown. To improve the evaluation of the criterion, the program should be able to tell whether precision or high motor skills are required from the operator. To distinguish whether high precision is needed it could be beneficial to include the allowed tolerances from RD&T.

If the changes from the discussion would be included in the manual assessment, because there are some of the HC criteria movements not performed in the simulation, the result would change to Table 6.1. This is because the simulation is simpler in comparison to how the assembly is performed in reality, and therefore missing the steps of fastening the components for example. The result in Table 6.1, is including both yes and no if one HC criterion has both, but the answers most common are in bold and if the HC criterion differs from the manual assessment the cell is red. The similarities between the simulation and manual assessment would differ between three to five criteria depending on the answer for criteria five and six. In comparison to the original result, see Table 4.4 and Table 4.5 where the rear lamp differed with two to three criteria and the bumper differed with four to five criteria, the result for the rear lamp is significantly inferior.

The validation of the program is influenced by the fact that it is not fully developed and is only a beta version, where out of seven criteria, three of them are static (criteria 1, 7, and 9), two of them provide the same result (criteria 3 and 11) and it is only a small variation in two of them (criteria 5 and 6). It is important to further tune the assembly complexity criteria evaluation to make the program function produce a better result.

Table 6.1: The remade validation if the manual assessment was changed. If the simulation differs from the manual assessment the cell is colored red.

Part	Type	HC 1	HC 3	HC 5	HC 6	HC 7	HC 9	HC 11
Rear lamp	Sim.	No	Yes	**Yes** No	**Yes** No	Yes	Yes	No
	Manual assmt.	No	No	No	No	No	No	No
Bumper	Sim.	No	Yes	**Yes** No	**Yes** No	Yes	Yes	No
	Manual assmt.	No	No	No	No	No	No	No

6.2 Improvements

The suggested improvements in Section 4.3, are based on observations from the performed validation and from the interviews. As described in Figure 4.2, none of the interviewees had tested the program and only two of them had seen demos of the program. This had an impact on the result because it obstructed the possibility of retrieving specific improvements directly linked to the combined program. So, the improvements suggested are therefore limited in perspective and do not provide a broad picture of the opinion of the different groups. However, this limitation created an opportunity, where the interviewees could give suggestions on desired functions of the program not influenced by what already exists and therefore could think more broadly. This was based on only the short description of the program's purpose and functions provided by the interviewers.

The manufacturing sites connected to CEVT often have more complex assembly than what is currently possible in the combined program, as stated in Table 4.6. To ensure that the program will be useful at CEVT, the simulated assembly operations that are possible to simulate need to have a complexity level similar to the ones made by operators in the factories. In case the simulation program differs too much from reality, it may not produce a reliable result.

6.3 Interviews

For the performed interviews there exist several sources of error, which affected the result. In the different groups the interviewees were divided into, the number of people in each group was unevenly distributed. As presented in Table 3.3, geometry was six people, manufacturing two, PQ one, and the designers two. The reason geometry is predominant is because many of them work with RD&T, which is an important part of the combined program. Furthermore, the people had different roles and therefore provided different perspectives on the subject. The desirable would have been to have interviewed an equal amount from manufacturing, but it was limited by the number of people working with IPS IMMA. PQ and designer were intended to be smaller groups, where the intention was to broaden the perspective from groups not specifically working with the program, but potentially using or being affected by the result.

In the analyzing process of the interviews, two methods were used when organizing the codes, specifically the third hierarchy of codes. For categories communication, assembly complexity, and work process, the third codes were directly sorted after the questions asked, in comparison to the category RD&T/IPS IMMA, which was organized after the theme. The reason for this difference was the approach or purpose of the question. Even if the interviews were semi-structured, some of the categories had a more quantitative approach or qualitative, which was the main deciding factor for the structure of the third order codes.

There are certain sources of errors that can be found during the interviews. When questions were asked about the ergonomics, it was not always specified that the questions intended assembly ergonomics for the operators in the production plant. Therefore, some interviewees may have understood the question in another way than what was intended and thereby given a misleading answer.

In the interviews, multiple interviewees mentioned that the company has had a reorganization recently. This was noticeable when questions were asked regarding the knowledge of other people's responsibility or work titles. In this project a part of the result was to map the communication between the different departments and this was made more difficult when the interviewees were unsure and could give contradicting answers to each other. In Section 2.6, about team efficiency, knowing your role and your team members' role is listed as an important factor for team efficiency.

6.4 Implementation in Work Process

In order to improve the support for the suggestions, it could have been beneficial to add more interview questions regarding a potential implementation. That could have given more specific support to the suggestions. In addition, more specific interview questions could also have given a more nuanced view of which meetings are suitable for the discussion and at which gate in the work process this analysis should be conducted. Instead the suggestions were mainly based on the original interview answers and discussions with the company supervisor.

Different ways to implement the program were presented. However, it is recommended to choose one clear manner to conduct it, to facilitate team efficiency. In the suggestion, specific details, such as meetings for handling the communication and time in the work process are suggested. That is, to facilitate team efficiency, as described in Section 2.6. The attributes in the different departments can be considered a team, because they are groups who are responsible for achieving an outcome. It is also stated that clear roles are important. Therefore the company shall clearly state which employee is responsible for what throughout all the departments. Moreover, the processes should also be clear to be able to reach an efficiency, which further motivates including specific meetings and analysis at specific points in time.

There were two main reasons why the meeting VIM was not suggested as a meeting for information transfer between geometry and manufacturing feasibility. Firstly, since the level of the meeting appears to focus more on common concepts and not on specific parts, the analysis might be too detailed. Secondly, the manufacturing is in the current version of the program not suggested to conduct the analysis. Which meeting that should be selected should also depend on the department, as different departments use different meetings differently. However, as previously stated, a specific meeting should be chosen and all concerned should be aware when it takes place.

In Section 5.3, there are different manners suggested in which it might be possible to use the result. However, in the suggestions it is unclear how to actually use the SUM (RMS) value, as there is not yet any research to support it. This is also mentioned in the Section 4.3.2, where the interviewees expressed confusion over how the result, the SUM (RMS), would be used. Therefore, the next step should therefore be to continue with research on how to handle this result. A potential suggestion is to decide a limit on what is the maximum number the SUM (RMS) value is allowed to be, and if the SUM (RMS) value exceeds that value, further review is needed.

If a person with knowledge in RD&T and not IPS IMMA performs the analysis, it is easier to choose an automatic grip, as it may be difficult to make a manual grip. However, the automatic grip function is currently not optimal and needs to be improved. In case the grip function would not be perfected until the program is implemented, there would be a need for an even closer communication, as representatives from the manufacturing group would be needed to help with that. A potential development of the program if the automatic simulation is too limited, is that a geometry engineer could load a more complex IPS IMMA simulation created by a manufacturing engineer, into the combined program in RD&T, to achieve a better result to the analysis.

6.4.1 Implementations in Work Process after Improvements

If the suggested improvements of the program from the result were implemented, it would enable new possibilities for the implementation in the work process. Some of these are presented in this section.

If the suggestion from G2 would be included, that the result would be a variance that can be added to the variance calculated in RD&T. This is an alternative to the SUM (RMS) value that is currently given as a result by the program. The benefit of having a variance would be that the company already has experience working with such results. However, since there is currently no manner to find a specific variance, the SUM (RMS) value could be more beneficial as it is already available.

The less digital and more specific the results from the program are, the easier it would be to give instant feedback to a designer, for example if the responsible for conducting the analysis is a support function at the design departments. Furthermore, some feedback could be possible to deliver directly to the designers from geometry, in order to minimize the communication loop. That feedback could specifically include the potential problems, to make it possible to work with. In other cases, it would be important that the feedback passes the manufacturing feasibility department, which has experience with working with feedback about making a product more feasible to assemble.

In Table 4.7, it is described that the connection potentially could be used to facilitate the communication between geometry and manufacturing through enabling sending the results between the programs. That could facilitate the collaboration between RD&T users and IPS IMMA users, who could send the simulation files between each other. Furthermore, it is more beneficial to have the complexity criteria to support potential ideas, instead of gut feeling, which is mentioned in Section 4.4.6. That is, because it could be handled in a more structured manner.

7
Conclusion

In this section, the conclusions of this master thesis are presented with the three research question described in Section 1.4.

7.1 Research Question One

> *Can the function that assesses the assembly complexity in the combined RD&T and IPS IMMA be validated for the rear bumper and rear lamp?*

For the program to be validated, the assessment from the simulation would need to be the same or almost the same as the manual assessment. The result for the simulation of the rear lamp in Section 4.2, presents four or five out of the seven evaluated criteria to be the same as the manual assessment, which could be a promising result. However, the bumper only has two to three out of seven evaluated criteria matching the manual assessment. When discussing the tuning based on which sequences actually were included in the simulation compared to the manual assessment, a new Table 6.1 was done, showing the simulation was not the same three to five out of seven. Therefore it is concluded that the function that assesses the assembly complexity in the combined RD&T and IPS IMMA, can not be validated for the rear bumper and rear lamp.

7.2 Research Question Two

> *What are the potential improvements for RD&T/IPS IMMA?*

Potential improvements of the combined program RD&T/IPS IMMA were found, both through using the program during the validation and through the interviews. The potential improvements found during the validation mainly concerned difficulties discovered while performing a simulation. The improvements suggested from the interviews came from both people who had seen a demo from the program and people who only had received a short explanation. The feedback included uncertainty about how the result should be used and difficulties regarding the grip. The improvement suggestions from the interviewees who had not used the program consisted mainly of desired functions of the program.

7.3 Research Question Three

> *How can RD&T/IPS IMMA be integrated into the product realization process at CEVT?*

In the report, the following suggestions of how to implement the combined program in the work process were identified. The manufacturing feasibility department shall continue to have responsibility for the manual assembly complexity related issues, but they will share the responsibility with the group conducting the analysis. The group conducting the analysis should be either geometry or a representative working with the design department. The communication shall take place either at the synchronization meeting or at the engineering meeting, depending on who is conducting the analysis. The program can be used by either using the feedback from specific criteria to improve the part or using the SUM (RMS) value to decide which part needs a thorough evaluation by manufacturing or for comparing solutions. The analysis should be conducted in time for the technical gate or at the design verification after the second and third gate. During a potential implementation of the combined program, the company should have a clear vision with the objectives of what shall be achieved and a strategy for the change. Furthermore, people who are influential in the workplace would need to support the change. It is important to have people interested in working with the program who conducts the analysis.

7.4 Further Development and Recommendation

The overall conclusion of the research questions is that the program can not be validated right now, but if some of the potential improvements are implemented and the development of the program is continued, it can be a beneficial tool for working with manual assembly complexity affecting the geometric quality. To continue developing the program, the first step is to improve the tuning of the criteria, investigate whether the assembly operation can include several movements and how the automatic grip position is decided. Aside from the further development of the program, there exist several others of potential further developments.

In order to use the combined program in an efficient manner, it is important to investigate how to beneficially handle the result, the SUM (RMS) value in particular. Currently, there is no way to decide whether a SUM (RMS) value is acceptable or not. Therefore, this is recommended to be further investigated in order to achieve the best prerequisites for use. Moreover, in a validated and well-functioning version of the program it could be possible to utilize measuring points from inspection data of finished cars and compare it to the simulation. Thereafter, it would be interesting to see whether there is any correlation between the movement that the manikin makes and an increased variance at a measuring point. An example could be to see whether the action of a manikin placing the hand on the vehicle leads to a higher variance in inspection data.

Bibliography

Alford, D., Sackett, P., & Nelder, G. (2000). Mass customisation — an automotive perspective. *International Journal of Production Economics*, *65*(1), 99–110. https://doi.org/10.1016/S0925-5273(99)00093-6

Allen, T. T. (2010). *Introduction to engineering statistics and lean sigma: Statistical quality control and design of experiments and systems* (2nd ed.). Springer, London. https://doi.org/10.1007/978-1-84996-000-7

Apperbaum, S., Habashy, S., Malo, J.-L., & Shafiq, H. (2012). Back to the future: Revisiting kotter's 1996 change model. *Journal of Management Development*, *31*, 764–782. https://doi.org/10.1108/02621711211253231

Arvidsson, M., & Gremyr, I. (2008). Principles of robust design methodology. *Quality and Reliability Engineering International*, *24*(1), 23–35. https://doi.org/10.1002/qre.864

Axelsson, J. (2000). Quality and ergonomics management - Toward an Emerging Integrated Paradigm -. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *44*(12), 2-467-2–470. https://doi.org/10.1177/154193120004401208

Bell, E., Bryman, A., & Harley, B. (2019). *Business research methods* (5th ed.). Oxford University Press.

Berlin, C., & Adams, C. (2017). *Production Ergonomics: Designing Work Systems to Support Optimal Human Performance*. Ubiquity Press. https://doi.org/doi.org/10.5334/bbe

Cameron, E., & Green, M. (2020). *Making sense of change management: A complete guide to the models, tools and techniques of organizational change* (5th ed.). Kogan Page.

Cavique, M., Gabriel-Santos, A., & Mourão, A. (2021). Mapping in design. In N. P. Suh, M. Cavique, & J. T. Foley (Eds.), *Design Engineering and Science* (pp. 255–284). Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-030-49232-8

CEVT. (2021a). *Redefining automotive engineering*. https://www.cevt.se/what-we-do/

CEVT. (2021b). *We enjoy getting great things done*. https://www.cevt.se/who-we-are/

Chalmers. (2019, October 2). *Analys med manikin för bättre geometrisk kvalitet vid manuell montering (AMIGO) [analysis with manikin for better geometric quality during manual assembly]*. https://www.chalmers.se/en/projects/Pages/Analys-med-manikin-fQr-bQttre-geometrisk-kvalitet-vid-manuell.aspx

Denscombe, M. (2014). *The good research guide: For small-scale social research projects* (5th ed.). Open University Press.

Desai, D. K. (2010). *Six sigma*. Himalaya Publishing House.

Dieter, G. E., & Schmidt, L. C. (2013). *Engineering design* (5th ed.). McGraw-Hill.

Eklund, J. (2001). A developmental quality approach for ergonomics. *Proceedings of the SELF-ACE 2001 Conference – Ergonomics for changing work*, 26–38. https://www.researchgate.net/profile/Joergen-Eklund/publication/239589177_A_DEVELOPMENTAL_QUALITY_APPROACH_FOR_ERGONOMICS/links/00b7d52815816c7247000000/A-DEVELOPMENTAL-QUALITY-APPROACH-FOR-ERGONOMICS.pdf

Falck, A.-C., Ortengren, R., & Hogberg, D. (2010). The Impact of Poor Assembly Ergonomics on Product Quality: A Cost-Benefit Analysis in Car Manufacturing. *Human Factors and Ergonomics In Manufacturing & Service Industries*, *20*(1), 24–41. https://doi.org/10.1002/HFM.20172

Falck, A.-C., Örtengren, R., & Rosenqvist, M. (2014). Assembly failures and action cost in relation to complexity level and assembly ergonomics in manual assembly (part 2). *International Journal of Industrial Ergonomics*, *44*(3), 455–459. https://doi.org/10.1016/j.ergon.2014.02.001.

Falck, A.-C., Örtengren, R., Rosenqvist, M., & Söderberg, R. (2016). Criteria for assessment of basic manual assembly complexity. *6th CIRP Conference on Assembly Technologies and Systems (CATS)*, 424–428. https://doi.org/j.procir.2016.02.152

Falck, A.-C., Örtengren, R., Rosenqvist, M., & Söderberg, R. (2017). Proactive assessment of basic complexity in manual assembly: development of a tool to predict and control operator-induced quality errors. *International Journal of Production Research*, *55*(15), 4248–4260. https://doi.org/10.1080/00207543.2016.1227103

Falck, A.-C., & Rosenqvist, M. (2014). A model for calculation of the costs of poor assembly ergonomics (part 1). *International Journal of Industrial Ergonomics*, *44*(1), 140–147. https://doi.org/10.1016/j.ergon.2013.11.013

Frey, B. (2018). The sage encyclopedia of educational research, measurement, and evaluation. *Sage publications*. https://doi.org/10.4135/9781506326139

Frohm, J., Lindström, V., Stahre, J., & Winroth, M. (2008). Levels of Automation in Manufacturing. *Ergonomia - International Journal of Ergonomics and Human Factors*, *30*(3), 1–28. http://www.researchgate.net/publication/255793362

Given, L. M. (2008). The sage encyclopedia of educational research, measurement, and evaluation. *Sage publications*. https://doi.org/10.4135/9781412963909

Hanson, L., Högberg, D., Carlson, J. S., Bohlin, R., Brolin, E., Delfs, N., Mårdberg, P., Gustafsson, S., Keyvani, A., & Rhen, I.-M. (2014). Imma-intelligently moving manikins in automotive applications. *Proccedings of ISHS 2014, Third International Summit on Human Simulation*. https://www.diva-portal.org/smash/get/diva2:751754/FULLTEXT01.pdf

Harrison, R. L. (2010). Introduction to monte carlo simulation. *AIP Conference Proceedings*, *1204*, 17–21. https://doi.org/10.1063/1.3295638

Hexagon. (2022). *CMM probes and sensors*. Retrieved February 25, 2022, from https://www.hexagonmi.com/en-US/products/coordinate-measuring-machines/cmm-sensors

Hu, S. J. (2013). Evolving Paradigms of Manufacturing: From Mass Production to Mass Customization and Personalization. *Procedia CIRP*, *7*, 3–8. https://doi.org/10.1016/J.PROCIR.2013.05.002

IPS AB. (n.d.). *IPS IMMA*. https://industrialpathsolutions.se/ips-imma

Kar, A. K. (2000). Linking axiomatic design and taguchi methods via information content in design. *First International Conferene on Axiomatic Design*, 219–224. https://axiomaticdesign.com/technology/icad/icad2000/icad2000_033.pdf

Kim, S.-G. (2014). Axiomatic design. In The International Academy for Production Engineering, L. Laperrière, & G. Reinhart (Eds.), *CIRP Encyclopedia of Production Engineering*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-20617-7_6441

Kondalkar, V. G. (2009). *Organization development*. New Age International Ltd.

Lien, T. K. (2014). Manual assembly. In The International Academy for Production Engineering, L. Laperrière, & G. Reinhart (Eds.), *CIRP Encyclopedia of Production Engineering*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-20617-7_6624

Lööf, J., Hermansson, T., & Söderberg, R. (2007). An efficient solution to discrete least-cost tolerance allocation problem with general loss function. In J. K. Davidson (Ed.), *Models for computer aided tolerancing in design and manufacturing: Selected Conference Papers from the 9th CIRP International Seminar on Computer-Aided Tolerancing, held at Arizona State University, Tempe, Arizona, USA, 10-12 April, 2005* (pp. 115–124). Springer, Dordrecht, the Netherlands. https://doi.org/10.1007/1-4020-5438-6

Matache, G., Dragan, V., Puscasu, C., Vilag, V., & Paraschiv, A. (2015). A comparison between 3d scanning and cmm dimensional inspection of small size gas turbine. *Advanced Materials Research*, *1128*, 347–352. https://doi.org/10.4028/www.scientific.net/amr.1128.347

Okes, D. (2009). *Root cause analysis: The core of problem solving and corrective action*. ASQ Quality Press.

RD&T Technology AB. (n.d.). *The tool RD&T*. http://rdnt.se/software-tool/

Rosenqvist, M., Falck, A., & Söderberg, R. (2012a). Geometry assurance versus assembly ergonomics - comparative interview studies in five manufacturing companies. In S. J. Hu (Ed.), *Technologies and systems for assembly quality, productivity and customization: Proceedings of the 4th CIRP Conference on Assembly Technologies and Systems* (pp. 101–104).

Rosenqvist, M., Falck, A., & Söderberg, R. (2012b). Robust design and geometry assurance considering assembly ergonomics. *Proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition IMECE2012*. https://doi.org/10.1115/IMECE2012-86267

Rosenqvist, M., Falck, A., Wärmefjord, K., & Söderberg, R. (2013). Operator related causes for low correlation between cat simulations and physical results. *Pro-*

ceedings of the ASME 2013 International Mechanical Engineering Congress & Exposition IMECE2013. https://doi.org/10.1115/IMECE2013-62678

Rosenqvist, M., Falck, A.-C., Lindqvist, L., & Söderberg, R. (2014). Geometrical robustness analysis considering manual assembly complexity. *Procedia CIRP*, *23*, 98–103. https://doi.org/10.1016/j.procir.2014.10.072.

Sargent, R. G. (2010). Verification and validation of simulation models. *Proceedings of the 2010 Winter Simulation Conference*, 166–183. https://doi.org/10.1109/WSC.2010.5679166

Scallan, P. (2003). *Process planning: The design/manufacture interface*. Elsevier.

Schlesinger, S., Crosbie, R. E., Gagné, R. E., Innis, G. S., Lalwani, C. S., Loch, J., Sylvester, R. J., Wright, R. D., Kheir, N., & Bartos, D. (1979). *Terminology for model credibility*. SCS TECHNICAL COMMITTEES. https://journals.sagepub.com/doi/pdf/10.1177/003754977903200304

Söderberg, R., & Johannesson, H. (1999). Tolerance chain detection by geometrical constraint based coupling analysis. *Journal of Engineering Design*, *10*(1), 5–24. https://doi.org/10.1080/095448299261399

Söderberg, R., Lindkvist, L., & Carlson, J. S. (2006). Virtual geometry assurance for effective product realization. *1st Nordic Conference on Product Lifecycle Management - NordPLM'06*, 75–88. https://www.researchgate.net/publication/229021917

Söderberg, R., Lindkvist, L., Wärmefjord, K., & Carlson, J. S. (2016). Virtual geometry assurance process and toolbox. *Procedia CIRP*, *43*, 3–12. https://doi.org/10.1016/J.PROCIR.2016.02.043

Suh, N. P. (2005). *Complexity: Theory and applications*. Oxford university.

Suh, N. P. (2021a). How do we design? In N. P. Suh, M. Cavique, & J. T. Foley (Eds.), *Design Engineering and Science* (pp. 72–116). Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-030-49232-8

Suh, N. P. (2021b). Introduction to design. In N. P. Suh, M. Cavique, & J. T. Foley (Eds.), *Design Engineering and Science* (pp. 1–33). Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-030-49232-8

Swift, K., & Booker, J. (2013). *Manufacturing process selection handbook*. Butterworth-Heinemann. https://doi.org/10.1016/B978-0-08-099360-7.00010-0

Tseng, M. M., Wang, Y., & Jiao, R. J. (2017). Mass customization. In The International Academy for Produ, L. Laperrière, & G. Reinhart (Eds.), *CIRP Encyclopedia of Production Engineering*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-35950-7_16701-3

Wärmefjord, K., Carlson, J. S., & Söderberg, R. (2009). A measure of the information loss for inspection point reduction. *Journal of Manufacturing Science and Engineering*, *131*(5), 0510171–0510176. https://doi.org/10.1115/1.4000105

Wärmefjord, K., Söderberg, R., Lindau, B., Lindkvist, L., & Lorin, S. (2016). Joining in nonrigid variation simulation. *Computer-aided technologies - applications in engineering and medicine*. IntechOpen. https://doi.org/10.5772/65851

Wärmefjord, K., Söderberg, R., Lindkvist, L., Lindau, B., & Carlson, J. S. (2017). Inspection data to support a digital twin for geometry assurance. *ASME*

International Mechanical Engineering Congress and Exposition, Proceedings (IMECE), *2*. https://doi.org/10.1115/IMECE2017-70398

Zimmer, S. (2021). Change Management. *Salem Press Encyclopedia*.

Zipkin, P. (2001). The Limits of Mass Customization. *MIT Sloan Management Review*, *42*(3), 81–87.

A

Interview Questions

The interview questions was divided into five themes, where the questions was adapted to the position or department the interviewees belonged to. The themes was:

- Introduction
- Work tasks and work process
- Communication
- Assembly complexity
- RD&T/IPS IMMA

A.1 Interview Questions to all Interviewees

Introduction

1. Is it okay for us to record this interview? The recording will only be used by us when concluding the information and be removed when we are done, at the latest on 31th July 2022.
2. What is your name and work title?
3. Do you work or have you worked with RD&T or IPS IMMA?
4. Have you heard about the AMIGO project before, a combination of RD&T and IPS IMMA?
   (a) If not, describe the project shortly.

   AMIGO is a research project, where Chalmers and companies, like CEVT, have collaborated. The aim is to be able to use a manikin (a digital human model) to help determine the manual assembly complexity, to be able to increase the geometrical quality. A beta version of a software, combining RD&T and IPS IMMA, is made in the AMIGO project. Firstly, the regular RD&T is used in the combined program. Then an added function makes it possible to open IPS IMMA, which determines the assembly complexity and sends the result back to RD&T. During our master thesis project, we will validate this program for certain cases, give improvement suggestions and suggest how CEVT can use it in the work process. We are thankful for your contribution to our project.

Work process

5. Can you explain your typical everyday work tasks?
   (a) What is the main purpose of your work?
   (b) Can you explain the work process that you follow?
   (c) What is your meeting structure?
   (d) What kind of deliveries exist?
   (e) Are there any gates that are especially important for you?
   (f) Who is the receiver of your result?
   (g) Who do you need input from for your result?

Assembly Complexity

6. What does the term "Manual Assembly Complexity" mean to you and do you consider it in your work?

   (a) Our definition of manual assembly complexity:
   When we speak of Manual Assembly Complexity we mean specific factors that increase the likelihood for the operator to make mistakes. The factors increasing the manual assembly complexity have been divided into 16 complexity criteria in previous research. The basic complexity criteria includes criteria regarding how much knowledge is required from the operator, the variety of fitting demands, the number of options of which the assembly can be done, how concentration or memory intensive the tasks are and how physically and visually demanding the tasks are.
   (b) Do you currently consider this definition of assembly complexity in your work?

Ending

7. Is there anything that you think we should have asked you about within this area that we have not?

A.2 Interview Questions to People Working with RD&T

Communication

1. How is the communication with the people working with IPS IMMA/ergonomics?
   (a) What would you think about an extended collaboration?

Assembly Complexity

2. Do you think there is a connection between ergonomics and geometry quality?
   (a) If yes, describe the connection.
   (b) How do you currently work with it?
   (c) Have you seen any problem due to such a connection?
3. Are you involved in TCF:s (trim car final) IPS simulation?
   (a) Why/Why not?
   (b) How does that affect your understanding of assembly complexity of assembling different parts?

RD&T/IPS IMMA

4. Have you tried using the RD&T/IPS IMMA?
   (a) If yes, do you have any suggested improvements of the software?
5. What do you believe that you could gain from using RD&T/IPS IMMA in your work?
6. How would you be able to include a program like RD&T/IPS IMMA in your work?
7. Would you like to include a program like RD&T/IPS IMMA in your work?
   (a) Why/why not?
   (b) What functions would you like?

A.3 Interview Questions to Ergonomist or Working with IPS IMMA

Communication

1. How is the communication with the people working with RD&T?
   (a) What would you think about an extended collaboration?
   (b) How do you think such collaboration should work?
2. How is the communication with the designers?
   (a) What would you think about an extended collaboration?
   (b) How do you think such collaboration should work?
3. Do you have the possibility to affect the design of parts?
   (a) At which stage?
   (b) Would you like to be able to give feedback at an earlier stage?

Assembly Complexity

4. Do you think there is a connection between ergonomics and geometry quality?
   (a) If yes, describe the connection.
   (b) How do you currently work with it?
   (c) Have you seen any problem due to such a connection?

RD&T/IPS IMMA

5. Have you tried using the RD&T/IPS IMMA?
   (a) If yes, do you have any suggested improvements of the software?
6. What do you believe that you could gain from using RD&T/IPS IMMA in your work?
7. How would you be able to include a program like RD&T/IPS IMMA in your work?
8. Would you like to include a program like RD&T/IPS IMMA in your work?
   (a) Why/why not?
   (b) What functions would you like?

A.4 Interview Questions to Designers

Communication

1. How is the communication with the people working with IPS IMMA/ergonomics?
   (a) What would you think about an extended collaboration?
2. How is the communication with the people working with RD&T?
3. What do you think about the feedback for your designs/constructions?
4. When do you get feedback about ergonomics?
   (a) Would you prefer to get feedback earlier?
5. After you have done the final delivery of a design/construction and it has moved to industrialization, are you still involved in changes?

Assembly Complexity

6. Do you think there is a connection between ergonomics and geometry quality?
   (a) If yes, describe the connection.
   (b) How do you currently work with it?
   (c) Have you seen any problem due to such a connection?
7. Are you involved in TCF:s (trim car final) IPS simulation?
   (a) Why/Why not?

   (b) How does that affect your understanding of assembly complexity of assembling different parts?

RD&T/IPS IMMA

8. Do you have any interest in the functions of this program?
   (a) Why/Why not?
9. From which department would you like this kind of feedback?
   (a) Why/Why not?

A.5 User of Ergonomic/Geometry Information

A.5.1 Interview Questions to Perceived Quality

Communication

1. How is the communication with the people working with IPS IMMA/ergonomics?
   (a) How does the feedback process work?
2. How is the communication with the people working with RD&T?
3. How is your process for giving and receiving feedback?

Assembly Complexity

4. Do you think there is a connection between ergonomics and geometry quality?
   (a) If yes, describe the connection.
   (b) How do you currently work with it?
   (c) Have you seen any problem due to such a connection?
   (d) How do you work with that kind of problem?
5. Are you involved in TCF:s (trim car final) IPS simulation?
   (a) Why/Why not?
   (b) How does that affect your understanding of assembly complexity of assembling different parts?

RD&T/IPS IMMA

6. Do you have any interest in the functions of this program?
   (a) Why/Why not?
7. From which department would you like this kind of feedback?
   (a) Why/Why not?
8. Do you think that the RD&T/IPS IMMA can affect the DTS (dimensional target strategy)?

A.5.2 Questions to Manager

Communication

1. How is the communication with the people working with IPS IMMA/ergonomics?
   (a) What would you think about an extended collaboration?
2. How is the communication with the people working with RD&T?

Assembly Complexity

3. Do you think there is a connection between ergonomics and geometry quality?
   (a) If yes, describe the connection.
   (b) How do you currently work with it?
4. Are you involved in TCF:s (trim car final) IPS simulation?
   (a) Why/Why not?
   (b) How does that affect your understanding of assembly complexity of assembling different parts?

RD&T/IPS IMMA

5. Do you have any interest in the functions of this program?
   (a) Why/Why not?
6. From which department would you like this kind of feedback?
   (a) Why/Why not?

A.5.3 Questions to System Leader

Communication

1. How is the communication with the people working with IPS IMMA/ergonomics?
   (a) What would you think about an extended collaboration?
2. How is the communication with the people working with RD&T?

Assembly Complexity

3. Do you think there is a connection between ergonomics and geometry quality?
   (a) If yes, describe the connection.
   (b) How do you currently work with it?
4. Are you involved in TCF:s (trim car final) IPS simulation?
   (a) Why/Why not?
   (b) How does that affect your understanding of assembly complexity of assembling different parts?

RD&T/IPS IMMA

1. Do you have any interest in the functions of this program?
   (a) Why/Why not?
2. Have you tried using the RD&T/IPS IMMA?
   (a) If yes, do you have any suggested improvements of the software?
3. What do you believe that you could gain from using RD&T/IPS IMMA in your work?
4. How would you be able to include a program like RD&T/IPS IMMA in your work?
5. Would you like to include a program like RD&T/IPS IMMA in your work?
   (a) Why/why not?
   (b) What functions would you like?
6. From which department would you like this kind of feedback?
   (a) Why/Why not?

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