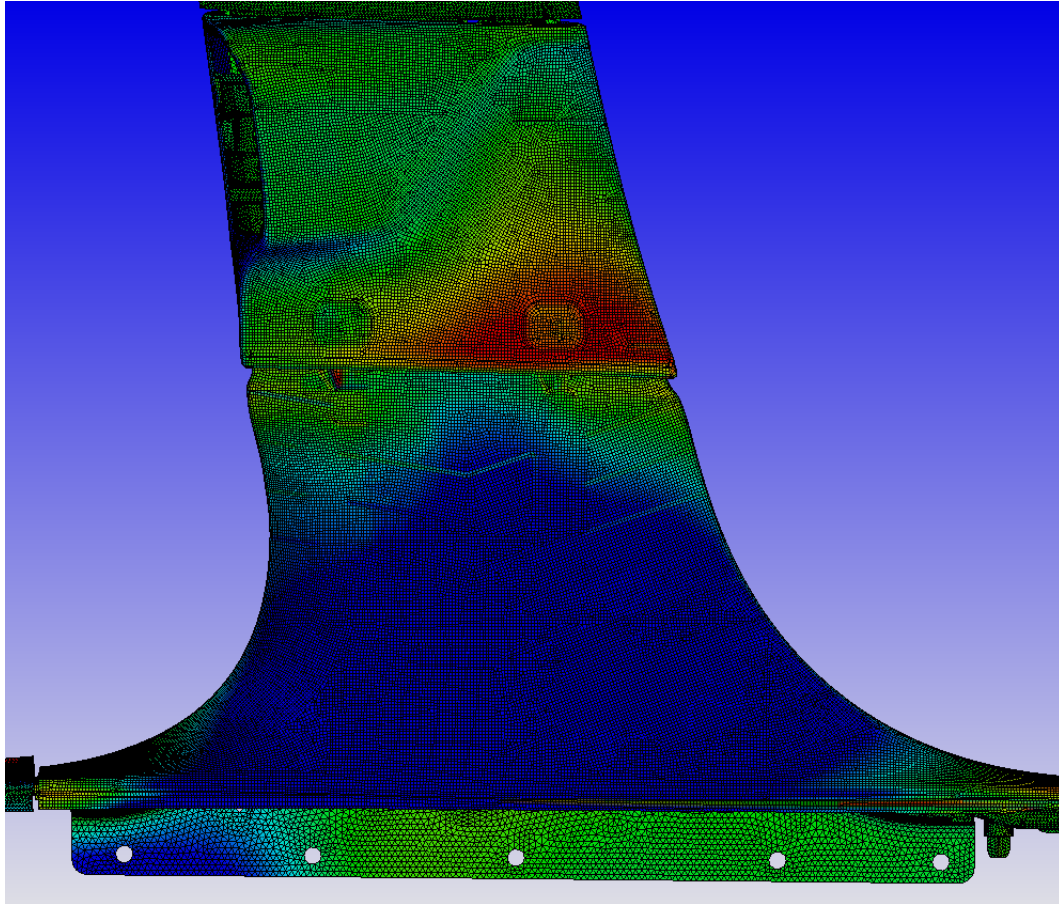




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Exploring Virtual Geometry Assurance for the Nominal Buck Verification Process at Polestar

Master's Thesis in Production Engineering

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MASTER'S THESIS 2025

Exploring Virtual Geometry Assurance for Nominal Buck Verification Process at Polestar

A work at Polestar in partnership with PE Geometry about exploring
the virtual possibilities for the nominal buck verification process

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Abstract

This thesis investigates the feasibility of digitalizing the nominal buck verification process at Polestar using virtual geometry assurance software such as RD&T. The nominal buck, a physical aluminum structure representing the ideal chassis geometry, is currently employed in Polestar’s verification process to evaluate the fit and alignment of interior and exterior vehicle components. Although the process is reliable with a high accuracy when it comes to asserting the geometric state of a part, the process is costly, time-consuming, and environmentally demanding. The objective of this study is to assess whether a virtual alternative can replace or complement the physical verification approach to improve efficiency, accuracy, sustainability, cost-effectiveness and flexibility.

Through a combination of literature reviews, industry interviews, and a detailed case study, the project explores the capabilities of RD&T for simulating geometric variation and part assembly. The digital method involves 3D scanning of physical parts, creating virtual fixtures, and applying statistical variation analyses to predict assembly behavior and compliance with tolerances. The research also includes a comparative analysis between the physical and digital approaches, highlighting advantages such as reduced lead times, lower material consumption, increased process flexibility, and enhanced data traceability.

The results suggest that a virtual verification process using RD&T can significantly improve the robustness and efficiency of the geometry assurance processes at Polestar, with additional sustainability benefits including waste reduction and streamlined global collaboration. However, challenges such as software limitations, implementation complexity, and required changes in workflow and skill sets must be addressed. This thesis contributes to the advancement of digital manufacturing practices and supports Polestar’s strategic sustainability and innovation goals.

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Hugo Kåhre
Samuel Persson
Gothenburg, 2025

List of Acronyms

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

3D	Three-Dimensional
BB	Black Box
BIW	Body In White
CAD	Computer-Aided Design
CAT	Computer-Aided Tolerancing
CMM	Coordinate Measuring Machines
CM4D	Coordinate Measurement for Dimensional Data
CNC	Computer Numerical Control
CSV	Comma-Separated Values
DFA	Design for Assembly
DFM	Design for Manufacturing
DFMA	Design for Manufacturing and Assembly
DMIS	Dimensional Measuring Interface Standard
DP	Design Parameter
FEA	Finite Element Analysis
FR	Functional Requirement
MIC	Method of influence-coefficients
MMC	Maximum Material Condition
MP	Measure Point
MSV	Machine Vision Systems
PCA	Process Capability Analysis
PDP	Product Design Process
PP	Pilot Production
PS	Project Start
PSDS	Polestar Development System
RD&T	Robust Design and Tolerancing
RDM	Robust Design Methodology
SPC	Statistical Process Control
TT	Tooling Trials
VF	Virtual Fixture
VP	Verification Prototypes

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1

Introduction

1.1 Background

In the beginning of the 20th century, mass production became a central theme in global manufacturing and thus also interchangeability where tolerances needed to be specified (Söderberg et al., 2016). Following the second world war the overall quality of products began to increase in Japan and then increased even further in the Western societies by the 1980's. By this time, all tolerancing were done physically using measuring tools and formulas. In pace with technological advancements, machines and software were developed to simulate different tolerancing processes to make it cheaper, easier and faster. Today, many companies — particularly in the automotive manufacturing industry — use these software tools to simulate various processes, such as variation analysis, contribution analysis, and stability analysis of their parts and assemblies. In modern terminology, these processes are typically grouped under the field of geometry assurance, particularly within the automotive industry. Consequently, geometry assurance will be the central focus of this thesis.

Polestar currently manufactures an aluminum bodywork model of cars in development called a nominal buck as the first step in their verification process. This is done to test how different interior and exterior parts fit when they are assembled together, as well as how fasteners should be placed in the car. All of this is currently done physically, leading to substantial cost and material usage, as well as extensive lead times. Depending on the standard of manufacturers, tolerances can differ, which with the current process are discovered at a quite late stage in the production chain. Additionally, if parts are within tolerances but screw-holes are slightly misplaced, fasteners occasionally need to be moved or re-engineered, resulting in even further delays. To potentially reduce lead times, increase efficiency, and decrease costs, Polestar wants to explore the possibility to conduct nominal buck tests as these in virtual environments instead, with help of Computer-Aided Tolerancing (CAT) tools such as Robust Design & Tolerancing (RD&T).

To give the project a clear objective aligned with sustainability initiatives, research questions are formulated around economic, technological, and environmental aspects. In discussions about digitalization initiatives within production environments, two key themes frequently emerge: cost reduction and increased efficiency. Additionally, waste reduction and changes in employment are also central concerns. By digitalizing the verification process, the need for a physical nominal buck is signif-

icantly reduced, leading to less material waste and contributing to both economic and environmental sustainability. However, digitalization may also affect workforce requirements, potentially altering the number of personnel needed. To explore these considerations in depth, six research questions have been developed, as outlined in Chapter 1.5.

1.2 Polestar

The history of the Polestar brand started in 1996 when a small Swedish team called Flash Engineering started building and racing purpose-built Volvo vehicles which were used in the Swedish Touring Car Championship (O'Steen, 2024). They later became Polestar Racing and became an official partner to the Volvo Cars brand. Volvo Cars fully acquired Polestar in 2015. In 2017, Polestar branched out and became their own independent company, as they released their first car model - Polestar 1 (Rabe, 2017). With this release they positioned themselves as a premier maker of electric and plug-in hybrid luxury cars (O'Steen, 2024). Polestar 1 was manufactured in Chengdu, China, and the last model was manufactured in 2021. An example of a Polestar 1 vehicle can be seen in Figure 1.1.



Figure 1.1: The Polestar 1 with a total system output of 609 horsepower (HP) and 1000 Nm torque (Polestar, 2025b).

Polestar currently have three models in their supply - Polestar 2, Polestar 3, and Polestar 4. Manufacturing is outsourced, as Polestar 1 and Polestar 2 (their 5-door liftback) have both been manufactured in China (Chengdu and Luqiao respectively) (Polestar, 2025c). Polestar 3 (the electric SUV) on the other hand, is manufactured in South Carolina, the United States (Polestar, 2025d). Polestar 4 is their SUV

coupé and is produced in Hangzhou, China, with additional production planned in Busan, South Korea, in 2025 (Polestar, 2025e). All manufacturing is therefore outsourced. However, their main office is located in Gothenburg, where 1156 employees are currently working (Allabolag, 2025). Polestar has sustainability as one of their core priorities, with clear sustainability goals for the next couple of years. By 2030, they hope to manufacture a completely climate neutral vehicle, and halve their greenhouse emissions per sold vehicle (Polestar, 2025a). By 2040 they hope to achieve climate neutrality throughout their whole value chain. Polestar is the main stakeholder in this project.

1.2.1 Polestar 5

The specific vehicle of interest during this thesis is Polestar's coming vehicle - Polestar 5, which is planned to be sold on the market by 2026. The Polestar 5 is produced in Chongqing, which means the nominal buck (which is explained in chapter 2.2) is also located there. All parts, data, and other references used during this thesis will refer to the Polestar 5. Figure 1.2 shows a prototype of the vehicle.



Figure 1.2: Prototype of the Polestar 5 at the 2023 Goodwood Festival of Speed, United Kingdom (Polestar, 2025f).

1.3 PE Geometry

PE Geometry are leading experts in the field of geometry assurance (PE-Geometry, 2025). The company was founded in 1999 by the current CEO, Peter Edholm, in Gothenburg. PE Geometry Inc, daughter company of PE Geometry, opened up in 2016 in North Carolina in the United States to serve their American customers. PE Geometry has their main office in Mölndal, and their employees work mostly as consultants for other companies, mainly customers within the automotive industry. For example, many geometry assurance processes at Polestar are outsourced to PE Geometry, which means that they play a crucial role in this project as both supervisors and stakeholders. PE Geometry states themselves that for them, "geometry assurance includes all processes that serve to create a geometrically robust and well defined product, both functionally and aesthetically". This is usually achieved by using advanced Three-Dimensional (3D) simulation software which allows for variation analysis in great detail.

1.4 Problem Statement

In Polestar's current design process, all tolerancing are performed either physically or with Computer-Aided Design (CAD) software. This entails that the digital model which is constructed is a nominal model, meaning it is a perfect model without deviations. As such, when simulating variations in software like RD&T the model represented will always be perfect. This will not be the case for manufactured parts. Since there is always noise and disturbances in machines used for production, the parts will always have slight variations compared to the nominal model. To enable a better understanding and more realistic simulation of parts and how they are situated as opposed to each other, the parts used in simulation model needs to be as close to the real life model as possible. Furthermore, because of the earlier mentioned variation in parts, engineers cannot be sure that all parts fit within the tolerances specified. This creates a problem for engineers to quickly analyze if batches are within tolerances or not.

1.5 Research Objectives & Questions

To be able to evaluate the results of this thesis, certain research objectives and questions need to be posed. These questions will be used to keep track of the goals for the report and finally clearly establish the conclusions of the thesis. There are two types of questions posed. The first is technical/economic questions which relate to the main problem at Polestar. Secondly, there are sustainability questions that relate to how Polestar would be sustainably impacted by solving the issue.

Technological & Economic Questions:

- **RQ1:** What are the advantages/disadvantages of simulating nominal buck geometry assurance within a virtual space like RD&T?

- **RQ2:** How do you ensure the most realistic simulation for nominal buck verification?
- **RQ3:** Can all parts be effectively simulated using a virtual nominal buck?
- **RQ4:** How would a transition to virtual geometry assurance impact Polestar?

Sustainability Questions:

- **RQ5:** How would waste be reduced by digitalizing the nominal buck verification process?
- **RQ6:** How would employees working with nominal buck verification be impacted by digitalizing the nominal buck process?

1.6 Scope and Limitations

The aim of this master's thesis is to evaluate the feasibility and potential benefits of digitalizing the nominal buck verification process using software tools such as RD&T. The outcome will guide Polestar's decisions regarding if virtual modeling of nominal buck verification is viable and how they should proceed with implementing it.

Certain limitations have had to be considered during the project. The most prevalent limitation is that the only geometry assurance software available is RD&T. This will not make it possible to compare different variation simulation software. Another limitation is the fact that the nominal buck is located at the Polestar production plant in Chongqing, China, making it impossible to carry out any tests with the nominal buck. Three plastic parts were used during the case study to demonstrate the digital method developed during this project. However, the project group only had access to these parts for one week, which was also a limitation.

1.7 Contributions of the Study

This thesis will contribute in several ways to Polestar's working methods regarding geometry assurance for nominal buck verification. Increasing Polestar's knowledge regarding virtual geometry assurance, realistic tolerance simulations and advantages as well as disadvantages will come to light. Furthermore, this thesis will contribute to research on how companies should and can develop their working methods toward more realistic virtual simulation within robust design and tolerancing software.

1.8 Outline of the Study

This thesis is organized into six chapters. Chapter 1 introduces the background, objectives, and scope of the study. Chapter 2 presents a literature study with a focus on geometry assurance, as well as important physical and digital technologies in relation to this. Chapter 3 describes the research methodology, detailing the

analytical framework, interview process, and case study design. Chapter 4 presents the results of the interviews, the description of the case study, and the comparative analysis between the physical and digital verification methods. Chapter 5 provides a discussion of the findings in relation to the research questions and broader industry implications. Finally, Chapter 6 concludes the study with a summary of key insights, limitations, and suggestions for future work.

2

Literature Study

This chapter presents the literature study that was conducted to find crucial information within the field of geometry assurance. Geometry assurance is the concept of ensuring that products are within quality tolerances, and includes all activities and tools needed to do so (Söderberg et al., 2016). Furthermore, related topics to this field such as current methods of geometry verification are also explored, which will pave the way for constructing a digital method at later stages.

2.1 Polestar's Production System

Polestar is developing and producing vehicles according to their core production system - the Polestar Development System (PSDS). The PSDS is used to design, develop, and produce products that are then delivered to their customers, which is achieved by balancing time, cost, and quality. The PSDS provides a generic framework of key milestones, gateways, phases, and deliverables to support the delivery of their vehicle program. The PSDS consists of distinct areas, each one specializing in governing crucial aspects of Polestar's business processes. An overview of the PSDS with its various departments can be seen in Figure 2.1.

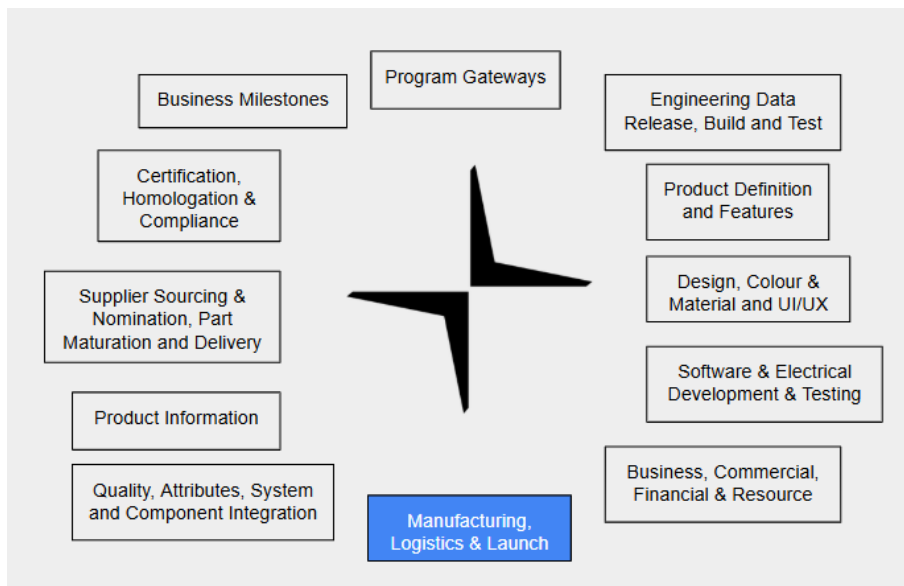


Figure 2.1: An overview of the PSDS with its important areas. Work is conducted within Manufacturing, Logistics & Launch in this project.

As can be seen, one area is Manufacturing, Logistics and Launch, where the area of manufacturing is handled by the department of Product & Process Manufacturing Engineering. They have the responsibility to work in partnership with the business to agree on product and process solutions, to allow the delivery of vehicles according to quality agreements, and to enable profitable manufacturing strategies. The department also has the responsibility of planning production and preparing plants for new products and processes, which also involves the tools and equipment necessary to do so. Product & Process Manufacturing Engineering consist of four function areas, one of them being Manufacturing Engineering Geometry Assurance. This department governs all processes related to verifying the geometries of parts assembled in a Polestar vehicle. This involves, for example, developing methods for part verification, which is currently done with help of a physical nominal buck. It is within this area that the project group will conduct work to improve Polestar's current verification process, and to assess the possibility to perform that verification with help of digital tools, either as a total replacement or an additional tool that may help improve the company's business operations. Polestar is also working according to four distinct phases during their development process. The first one is the Project Start (PS), a phase of early production runs to test new manufacturing processes and identify issues. The next phase is the Verification Prototypes (VP), which is when prototypes are built to verify the design and engineering aspects of their vehicles. The third phase is the Tooling Trials (TT), which consist of trials to test production tools and equipment. The fourth and last phase is the Pilot Production (PP), which consist of initial production runs using the finally developed production processes, tools, and equipment.

2.2 The Nominal Buck

The nominal buck is a framework of the car chassis where all dimensions are nominal (see Figure 2.2). Other names for the nominal buck is a master buck, body buck, etc. and the naming varies between automotive manufacturers. The nominal buck is called "nominal" because all dimensions of the nominal buck are close to perfect and closely resembles CAD data of the vehicle. Common material is either aluminum or steel, and Polestar uses aluminum for their nominal buck. A nominal buck is therefore constructed for each car model. Purchased or manufactured vehicle parts, both exterior and interior parts, are then physically inserted into the nominal buck, to visualize the fit of the parts in a nominal environment. To achieve this, fixtures and fasteners are used to hold the parts in place using attachment plates during measurement and analysis. Attachment plates are used, because when small design changes need to be implemented to an already manufactured nominal buck, the attachment plates can be re-machined instead. The nominal buck offers the possibility to analyze part dimensions and determine if they are within tolerances, both in terms of functionality and aesthetics. The perceiver, or worker, can then assume that the parts are either okay and deliver these to final assembly, or not okay and send them back to the supplier for reworking. The nominal buck is therefore a physical verification tool and an important step in the vehicle production chain.



Figure 2.2: One of Polestar’s nominal bucks. The photo has been brought from internal sources (Polestar, 2025).

2.3 Geometry Assurance in Manufacturing

Geometry assurance can be described as a number of activities, all contributing to minimizing the effect of geometric variations on a final product (Söderberg et al., 2016). This methodology is the base of the project and it is from this source that all other important methodologies and concepts will stem from. During the early twentieth century with the introduction of mass production, manufacturers realized that two products of the same kind may never be completely identical, due to the stochastic nature of manufacturing. Because of this, tolerance requirements are needed, as they direct focus to certain parts of a product that are more sensitive to geometric variations. Geometry assurance processes are implemented to ensure both functional and aesthetic qualities of a product (Rosenqvist et al., 2016). A product’s realization phase can be divided into three distinctive phases - the concept phase, the verification phase, and the production phase (Söderberg et al., 2016). This realization phase is visualized in Figure 2.3 below. Assuring that products are within geometrical tolerances is important within all these phases, to prevent that geometrical variations are detected at a much later stage in the product chain, where costs and environmental impact of remanufacturing can be problematic.

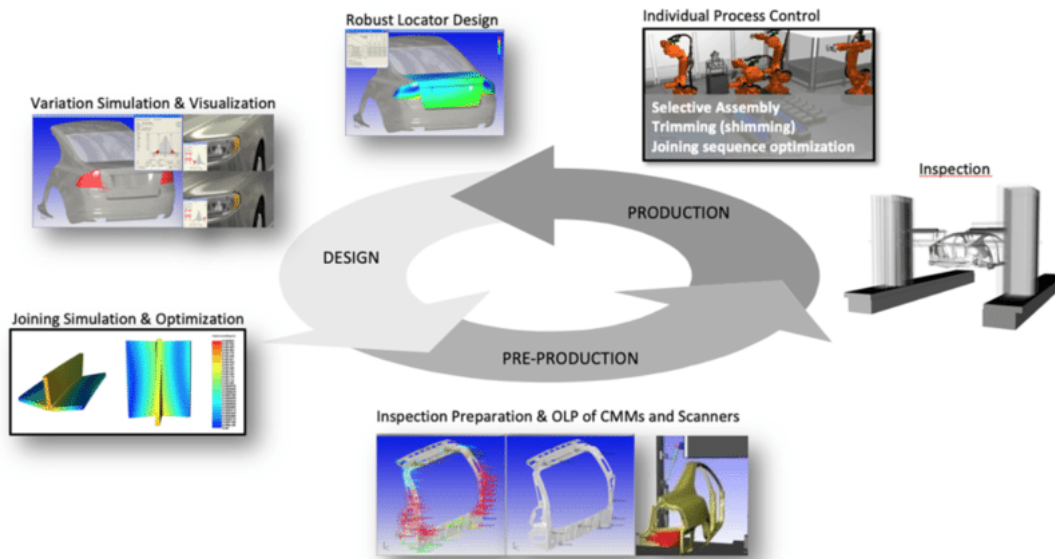


Figure 2.3: The different phases of a product’s realization phase, including typical activities within these (Söderberg et al., 2016).

The concept phase is the start of the product’s life cycle, when both product and production are conceptualized (Söderberg et al., 2016). At this stage, geometry assurance can be initiated by simulating product variations, which can give hindsight of future outcomes. Simulation is a robust tool in such situations, as realistic data can be implemented to assure that the model is realistic in the sense that it mimics the real world product and production. Statistical tolerance analysis can be used to predict how the product’s geometry may vary during production. During this stage, the visual appearance and functionality of the product can be optimized. For example, ensuring that the product is geometrically robust, which could be achieved by having an uncoupled design. In an uncoupled design, each output or Functional Requirement (FR), is controlled by only one output or Design Parameter (DP). An uncoupled design is much easier to control than an coupled design, as geometrical variations in one part (in an assembly) will not affect another part in that assembly. An uncoupled design therefore ensures that the design is geometrically robust, in other words, that the design is insensitive to variations. However, some authors mention that it may be difficult to create digital models of a complex manual assembly operation, as some assembly factors (such as assembly complexity), are not included in the digital models (Rosenqvist et al., 2016). The authors also mention that a study demonstrated that the correlation between digital CAT simulations and actual outcome in a production environment is low. Furthermore, assembly complexity seems to have a major impact on product quality.

In the verification phase, product and production are physically implemented and tested (Söderberg et al., 2016). As product design already has been concluded the important step of this stage is to focus on the efficiency of the production. The Computer Numerical Control (CNC) machines are programmed to manufacture the product according to design parameters, a process which needs to ensure that criti-

cal parts of a product are within tolerances.

Lastly comes the production phase, which is when all production processes are adjusted and product is in full production (Söderberg et al., 2016). To ensure product quality, geometrical dimensions and functionality need to be measured, especially after final production processes before product is being packaged and sent out to customers. The nominal buck process is used during the production phase, as it is a verification tool before parts are sent to final vehicle assembly. Thus it is within this phase that this master thesis project is focused. As the objective of this project is to digitalize an activity in Polestar’s geometry assurance process, it is worth mentioning the importance of data collection. As part of Industry 4.0 initiatives the continuous collection of data offers predictability and a higher rate of steadiness (Barton et al., 2024). Collected data can be measured throughout time and analyzing this creates an overview of production. This is one of the key advantages of digital tools compared to traditional physical measuring methods.

2.3.1 Core Methodologies in Geometry Assurance

A comprehensive understanding of geometry assurance requires familiarity with several key methodologies and concepts. Initially, it is essential to recognize how a product’s design can influence its sensitivity to geometric variation—both as an individual component and within a complete assembly. Additionally, the role of geometric tolerances must be considered, alongside the purpose of Statistical Process Control (SPC) processes, which is commonly employed by manufacturing organizations to enhance process stability and quality control. Lastly, the notion of perceived quality from the customer’s perspective is crucial, as it provides insight into the extent of geometric variation a product can exhibit before it negatively impacts the user’s perception and overall satisfaction. All of these concepts will be explained in this chapter.

2.3.1.1 Product Design

The importance of the product’s design must be considered when seeking to increase product quality. This is important to consider when studying the geometry assurance process at Polestar. Below is information regarding robust design principles and design for assembly & manufacturing.

Robust Design Principles

Variation in products affect their performance, which ultimately can lead to product failure, dissatisfied customers, the need for increased quality control, and added development and service costs, all of which impact the profit of the supplier (Ebro and Howard, 2016). Variation inflicts the intention of consistent behavior. Therefore, the design engineer should design the product in such a way that variation in functional behavior is minimized. The design engineer may come up with an entirely nominal product model, but as the world is always stochastic and two products of the same kind may never be completely geometrically identical, another important

task is to minimize the variation in functional performance. The sources of variation (noise sources) are commonly divided into three categories: environmental factors including variations in the conditions of use (external noise), deterioration including the aging of products (internal noise), and variation in production (unit-to-unit noise) (Torben Hasenkamp and Arvidsson, 2007). Each such noise affecting variation in performance can therefore arise in a specific phase of the product's life cycle. There are two ways to minimize noise in products. One approach is to eliminate them, which may be difficult as the noise factors might be unknown, costly, or even impossible to eliminate. The other approach is to design products in such a way that they are insensitive to variations, which is the core of Robust Design Methodology (RDM). The key idea is that, instead of trying to control the environment, the product should be designed in such a way that it is insensitive (robust) to the environment. This methodology has its roots in the work of Japanese engineer Genichi Taguchi during the 1980s (Andersson, 1997). As RDM focuses on the initial design of a product, it should be initiated early in the Product Design Process (PDP), as product design plays a key role in its potential for variation in performance. The important thing to have in mind is that products should be designed so they have a high level of geometrical robustness. Different examples of sensitive designs, and how these can be altered to be more robust, is demonstrated in Figure 2.4. As robust design principles focus on minimizing the sensitivity of products to variations in manufacturing processes, early tolerance analysis and front-loading of design processes are essential to achieve robust designs (Goetz et al., 2018). In this specific project, this is important to be aware of as different automotive parts will be studied in relation to each other, how they are interconnected and assembled. Even though the main task is to find an alternative, digital method to the current physical verification process, it is important have knowledge about the fact that geometrical robustness plays a key role in variation. If a specific model of a part has problems of variation between units, it may be because of machining settings, but it may also be that the design is not geometrically robust.

ID	Type of ambiguity	Example	Solution
A	Angled interface. Coupling between angle, width and position of part.		
C	Clearance < n*production_capability. Risk of an unwanted constraint due to part variations.		
D	Draft on interface element. Draft angle defines positioning.		
F	Flash. Flash acts as interface element. Misplacement of component.		
I	Intended not realized. Loss of overview e.g. wrt. tolerance and structural analysis		
L	Large surface. Increases demand on form tolerances.		
M	Multiple surfaces constrain same DOF. Loss of overview. Parasitic loads. Increase in tolerance demands.		
R	Round. Round acts as interface element. Misplacement of component.		
S	Shift (abrupt) of interface. Sudden change of contact point		

Figure 2.4: Examples of sensitive design and how these can be designed to be more robust (Ebro et al., 2012).

Design for Manufacturing & Assembly

Design for Manufacturing (DFM) is a discipline where the goal is to design products that are easy and cost-effective to produce (Bogue, 2012). Design for Assembly (DFA) is a closely related discipline, but with the goal of making the product(s) easier and more efficient to assemble. Together they are often referred to as Design for Manufacturing and Assembly (DFMA). These both disciplines are important when considering product quality. Products that are made easier to both manufacture and assemble are in need for less quality control processes. One typical DFA guideline is to minimize the number of parts in an assembly (Oh and Behdad, 2016). The idea is that more parts require more steps in an assembly, and thus requires more time, precision, and resources. It also requires more frequent contact with suppliers. One important DFA principle is therefore to remove unnecessary parts from an assembly, or joining parts together in the initial design. A case of such is demonstrated in Figure 2.5 below. There are many great examples of DFA initiatives in historical manufacturing settings (Bogue, 2012). Ford Motor Company have used many DFMA tools throughout their operations, training their engineers

in the DFA methodology. Ford is also requiring their vendors to conduct DFA analyses before submitting bids on subcontracted products. This means they make sure that all parts coming into their final assembly have successfully went through DFA assessments. Their operations involve gathering product designers, manufacturers, and suppliers, for regular meetings where both the conceptual design for their future products and products currently being manufactured are discussed. Ford's implementation of DFMA tools has resulted in significant benefits, including enhanced product quality and increased customer satisfaction. A key takeaway from these disciplines is the critical importance of the initial design of each component. In the case of a Polestar vehicle, which consists of thousands of individual parts, every component must be designed with efficient manufacturing and assembly in mind. These components are subsequently analyzed in later stages using CAD and simulation software. Integrating this approach within manufacturing processes ensures that a higher proportion of components will meet the required standards during nominal buck verification - whether the verification is conducted digitally or through physical methods.

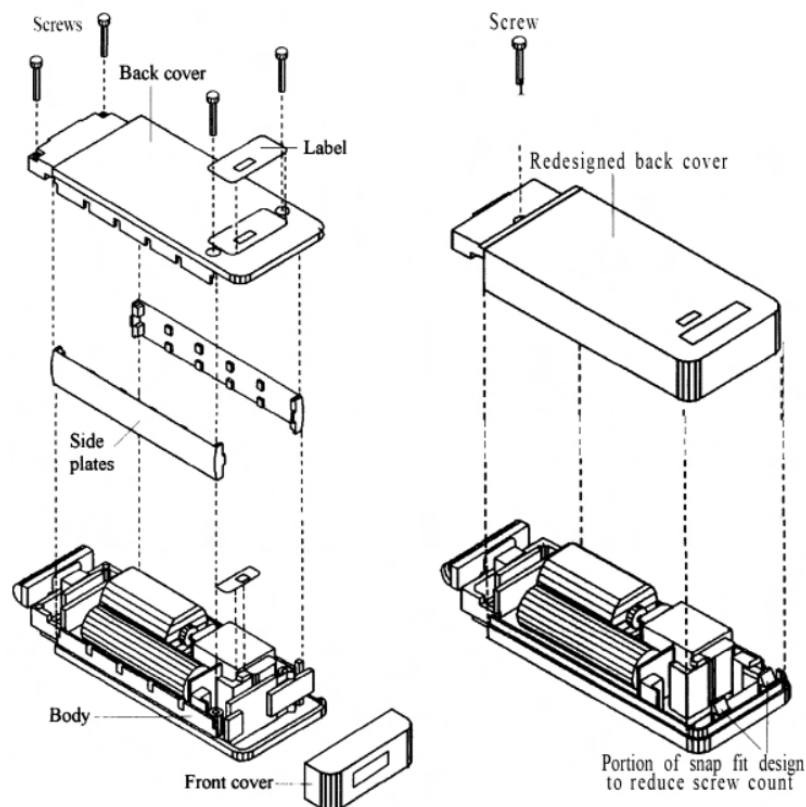


Figure 2.5: The Figure shows how the initial design of a product can be more or less suited for assembly. The design to the left have many screws and assembly steps, while the design to the right require much less number of screws and assembly steps. The ultimate goal is to assemble the body to the back cover, however, the differences in assembly process affects time, cost, and flexibility considerably (Disher, 2020).

2.3.1.2 Geometric Tolerances

Geometric tolerances are fundamental to geometry assurance, as they govern acceptable deviations from ideal geometry and are critical for maintaining product quality and functionality (Haberhauer, 2014). They provide a standardized framework that ensures mutual understanding between designers, manufacturers, and suppliers regarding geometric and dimensional accuracy. See Figure 2.6 for examples of geometric tolerances.

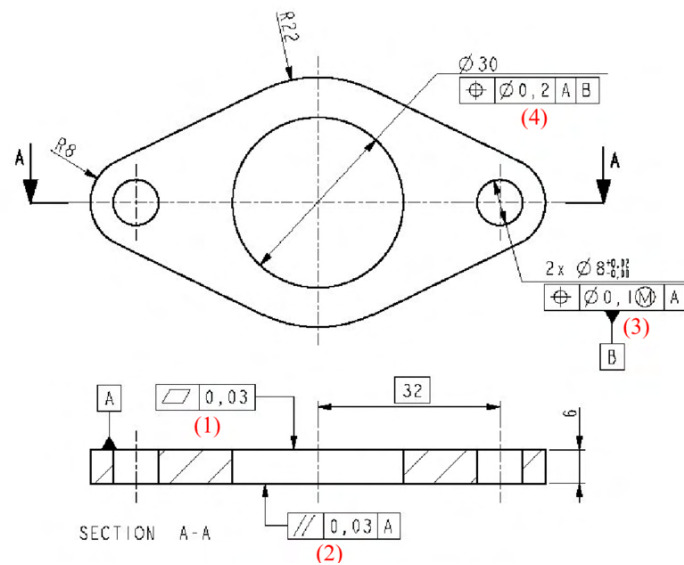


Figure 2.6: Examples of geometric tolerances (Pairel et al., 2007).

In modern product development, precise tolerancing is vital due to increased market competition and the need to reduce defects and production costs (Armillotta and Semeraro, 2011). Well-defined tolerances not only guide manufacturing but also directly influence downstream processes such as assembly feasibility, inspection complexity, and overall production efficiency. Moreover, they serve as documented assurance for customers, confirming that the product meets both functional and aesthetic requirements.

2.3.1.3 Statistical Process Control (SPC)

Statistical Process Control (SPC) is a term that covers a broad scope, and it includes many different activities intended to control a manufacturing process. The main objective of these activities is to control quality and decrease variation in production (Montgomery et al., 1994). In short, SPC looks for signals that represent assignable causes, which can be thought of as external disturbances that increase variation. It is often assumed that process data can be seen as a set of statistically independent observations that fluctuates around a constant mean. Each such observation is then considered to be either special cause noise or normal cause noise, depending on if they are within the upper and lower tolerance limits. In order to control the process, the special cause noise, or unnatural noise, need to be located and eliminated. An

example of a control chart demonstrating this can be seen in Figure 2.7. SPC is usually implemented as a "top-down" initiative, starting with upper management, going downward to improve general quality within the company. The purpose of SPC is to monitor production processes, which identifies certain signals that may arise, and eliminating these signals to minimize variability and maximize control. This includes any type of action a company takes to monitor, analyze, and address certain processes in their production systems. SPC operations can include tools such as control charts, Process Capability Analysis (PCA), or digital tools such as Machine Vision Systems (MSV), computer-based SPC systems, or even predictive maintenance (which has gained much attention in recent years). For example, in the automotive industry, this could include a company doing physical measurements of all parts coming in to final assembly - a constant monitoring of geometries and dimensions. This data can then be stored, which with physical measurements often is done manually, but it enables the possibility to track historic data, and assumptions and conclusions can be drawn about the process throughout time. Certain parts may have higher variability, and once the root cause of such varieties are addressed, the problem has been acknowledged and eliminated. This whole chain of event is a typical SPC process. This subject is of importance, as a digitalization of an geometry assurance process also involves digitalizing the SPC process. Once parts are measured and verified digitally, this opens up the possibility for storing and communicating data about variations effectively. This can be productively automated which reduces both cost and time.

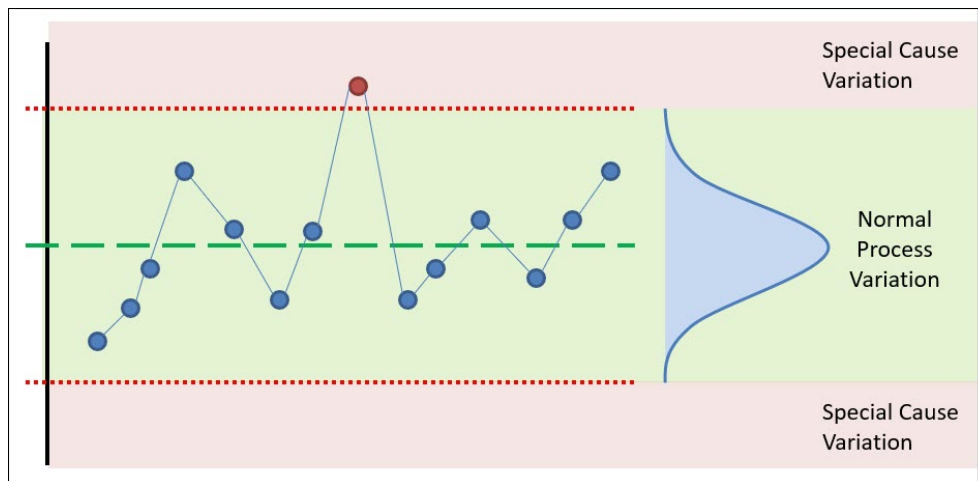


Figure 2.7: A control chart which categorizes data points based on normal cause variation and special cause variation (CQE, 2025).

2.3.1.4 Perceived Quality

Perceived quality is the expression customers feel toward purchased products. This is derived through touch, sight, sound, and scent, and it largely affects how customers feel about their suppliers (eg. brand loyalty). Research has shown that the choice to buy a new car is largely affected by several factors such as the brand value and the visual perception of interior and exterior parts (Tovillo et al., 2024).

The visual perception includes things such as color, which is explored deeply by Tovillo & colleagues. However, it also includes material quality and geometrical quality. The geometric outcome is an important factor that influences the perceived quality of the final car (Lindau et al., 2015). In another report, the authors has constructed a Perceived Quality Framework to characterize different units of quality perceptions, and rank them in importance according to what customers deemed to be most important (Stylidis et al., 2019). This framework can be seen in Figure 2.8. The visual quality took up 70% of the importance in perceived quality. Geometric variation involves gaps, flushes, and reflection alignments, and how these are perceived in interior and exterior parts. One important condition is "split lines", which are sometimes called gaps, which is commonly defined as the "relation between two mating parts over a specified distance". In the eyes of customers, such gaps can cause dissatisfaction. Geometry assurance is necessary in order to provide parts to assembly that has the required functionality, but also to look the intended way visually. The result of this is that a comprehensive geometry assurance process is needed in order to eliminate risks of failures, accidents, and customer dissatisfaction.



Figure 2.8: Perceived Quality Framework (Stylidis et al., 2019).

2.4 Geometry Assurance Tools

Even though the importance of digitalization has been underscored by several authors in recent years, it seems like most companies are yet to implement it in their geometry assurance processes (Lindau et al., 2020). For Body In White (BIW) sheet metal assemblies, physical verification of geometries is still the dominant method used in pre-series built to verify the outcome, before the start of the production phase. BIW is the stage in vehicle manufacturing in which the car's body frame has been joined together, before painting, trimming, and final assembly. The technologies and tools needed to achieve digital verifying methods are known, due to research in the field. There are also examples of companies who are in an early phase of implementing such tools on an production scale. This section will explain

how a digitalization of the geometry assurance process could be executed by using a range of different tools.

2.4.1 Measurement Technology

As mentioned in earlier sections, there are never two parts of the same kind that are completely identical. Companies therefore have to regularly measure the dimensions of their parts to ensure they are within tolerances. There are various ways of doing so but the most common today is using Coordinate Measuring Machines (CMM).

2.4.1.1 Coordinate Measuring Machine

CMM is widely used in industry for precise dimensional measuring, especially in mass production and automotive manufacturing (Ali, 2010). CMM measure object geometry by using Measure Points (MP) (Hocken, Pereira, et al., 2012). The MP are then stored in measurement file, which can be of different types such as CM4D, CSV, and DMIS. The two most common types of measurement tools are probes and articulated arms. These machines can be manual or automatic.

Probe

Probing can be done with either handheld devices or bridge-type CMM. Handheld probing is performed by an operator with a probe-mounted stylus (Ali, 2010). There are different probes of this type but the most common are touch-sensitive and react to any type of contact with another surface. By touching specific points of the object surface, discrete points are extracted resulting in a mapping of 3D space. Bridge-type-CMM, see Figure 2.9, are 3-axis machines that move in X, Y and Z direction in addition to the probe being able to rotate 360 degrees (Artkin, 2023). To create dimensional measurement, the obtained points are used to create geometries. To efficiently measure parts, the part measured need to be positioned in relation to the main axis. Similarly to the handheld stylus type probing, bridge-type CMM acquire its coordinates by touch-trigger of the probe. Moreover, if a CAD model of the part being measured is available, the scanning can be done automatically.



Figure 2.9: 3-axis probe-mounted bridge-type CMM (Wikimedia, 2009).

Articulated Arm

In recent years, articulated arm CMM has become more popular. This technology can be used in combination with both laser scanners and probes. By mounting a laser scanning device on the end of a robot arm with several joints, part surfaces can be efficiently scanned (Artkin, 2023). The arm is manually maneuvered by an operator. Because of its flexibility, which is similar to a human arm, the scanner can efficiently examine parts which are inaccessible to traditional CMM methods. Additionally, this technology captures several thousand points at a time, making it preferred in SPC applications because it provides comprehensive data for detecting variations and defects more accurately than traditional methods. It works by transmitting a laser beam onto a surface which is then reflected back to the scanner. The scanning location is then measured as the separation between the object and the scanner. The most widely used scanners are interferometers and Absolute Distance Meters (ADM) in which Spherically Mounted Retroreflector (SMR) are the most prevalent.



Figure 2.10: Scanner-mounted articulated arm CMM.

2.5 Software for Digital Verification

This section describes current and possible future software and technologies that can be used for digital verification of geometry assurance. As this thesis is limited to testing in RD&T, this will be the only digital software environment described.

2.5.1 RD&T

RD&T is a CAT software tool developed to simulate manufacturing and assembly variations before production begins (RD&T, 2025). The software has been used over 20 years within the automotive industry, working with original equipment manufacturers, suppliers and consultants. It works by applying statistical variation in tolerances on parts or assemblies which is then visualized. By using RD&T, several different concepts and assemblies can be quickly analyzed and compared, greatly reducing time needed for the design process. The main task of RD&T is ensuring robust designs that have a minimal variation when manufactured and are mainly used for non-rigid analysis. There are 3 basic functionalities in RD&T, namely variation analysis, contribution analysis, stability analysis, and engineering document generation.

To create model in RD&T which can be simulated, certain steps need to be performed. One of the most crucial steps to acquire the correct geometrical impact on the part in question is creating appropriate locators. Locators (or fixture locators) are reference points or physical features used to precisely position and secure a part during assembly, testing, or inspection. The locators are then used to create

a position system for the part. Positioning systems are digital representations of real-world alignment, used to simulate and validate product design, manufacturing processes, and testing procedures. This is used to lock the position of the part or sub-assembly in space to be able to perform different analyses.

Non-Rigid Variation Simulation

Parts that are produced for the automotive industry is more often than not, supposed to be flexible. Another word for parts that are flexible are non-rigid parts (Lindau et al., 2015). Non-rigid analysis of parts and assemblies aims to simulate parts according to their flexibility and bounce-back geometry. Using tools such as the variation analysis in RD&T, a more realistic result can be achieved for how the BIW parts will act (Wärmefjord, Söderberg, Lindau, et al., 2016). To achieve this analysis, Monte Carlo simulation is used. The simulation works by first utilizing a Finite Element Analysis (FEA) solver to create a initial mesh model of the non-rigid model. By studying the nodes in this mesh, displacement is determined. This in combination with the Method of Influence (MIC) makes it possible to find a linear relationship between part deviation and spring-back deviations allowing for thousands of simulations to be simulated quickly. The end result of a variation analysis presents the amount of parts which will be within tolerances in a normal distributed curve in regards to the upper and lower design limits. It also shows the deviation of the assembly or part as seen in Figure 2.11.

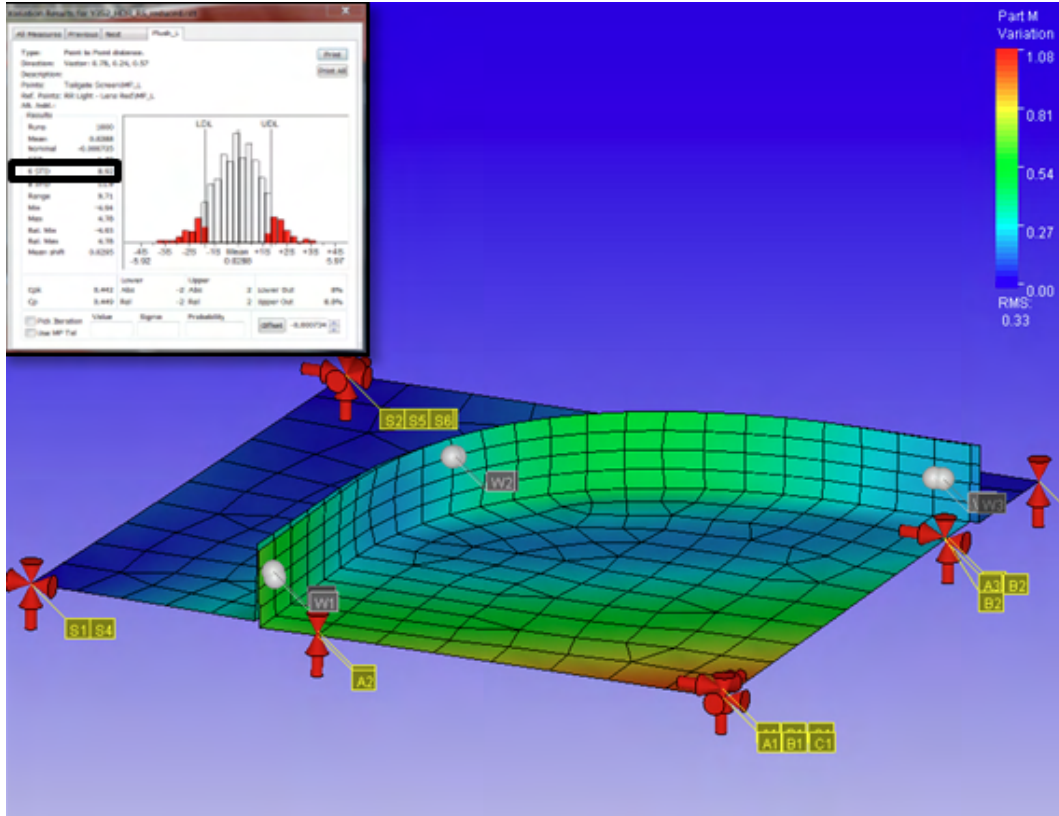


Figure 2.11: Variation analysis of part (RD&T, 2025).

Contact Modeling

In RD&T, contact modeling plays a vital role in ensuring the validity of assembly simulations, particularly when simulating interactions between flexible components. Contact analysis in RD&T involves identifying surface or edge interactions between adjacent parts and determining areas where physical interference or excessive clearance may occur (Lindau et al., 2015). The software supports automated contact detection through a specified range of values and tolerances, allowing for detailed visualization of surface interactions. Thus, RD&T facilitates the creation of critical gap and flush measures at contact points, providing a foundational understanding of how parts fit together within an assembly environment.

Material Temperature

Temperature-dependent material properties are a critical consideration in variation simulations involving dissimilar materials, particularly in assemblies that include plastic and metal components. Wärmefjord, Söderberg, and Lindkvist, 2016 highlights that parameters such as Young's modulus and thermal expansion coefficients must be defined for each part to ensure accurate results. These properties directly influence the stress distribution and holding forces in the final assembly. For example, plastic components typically experience greater thermal expansion than metals, which can lead to stress and geometric deformation. Moreover, Young's modulus itself is temperature dependent plastic becomes more compliant at higher temperatures and stiffer at lower ones. As shown in their case study, increasing the temperature results in decreased holding forces due to material softening, whereas lower temperatures led to increased forces. These findings underscore the importance of integrating thermal effects into RD&T simulations when evaluating clip fasteners or similar joining methods. Accurate simulation of these interactions supports robust design decisions.

Stability Analysis

The stability analysis function in RD&T allow the user to evaluate the geometrical robustness of an assembly or part design (RD&T, 2025). Using this analysis, the positioning of locators can be automatically or manually optimized, ensuring an optimal geometrical sensitivity. Stability analysis allows for early design changes, making later design faults less likely. The sensitivity is displayed using color coding of the parts visualized in Figure 2.12.

2. Literature Study

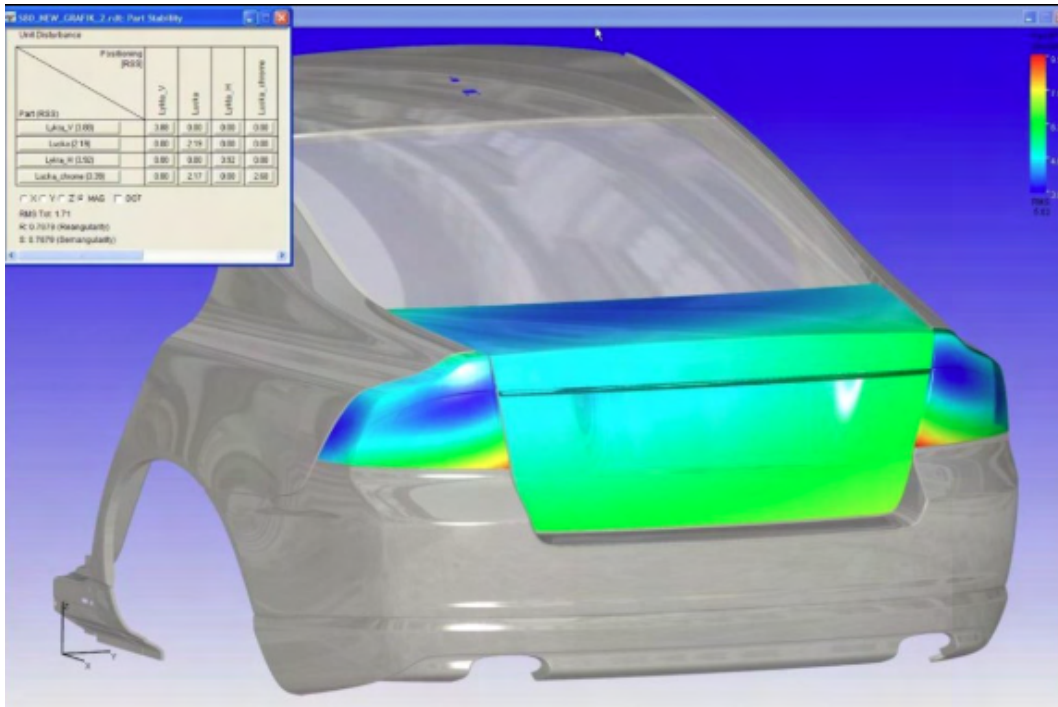


Figure 2.12: Stability analysis of a part (RD&T, 2025).

Contribution Analysis

From the variation and stability analysis general knowledge of how much the parts deviate can be acquired as previously shown. However, they do not display which tolerances play the most vital roles in the design. To get an understanding of each tolerances impact, the contribution analysis can be used (RD&T, 2025). The contribution analysis ranks the impact of tolerances in critical dimensions in percentage. Using this analysis, each tolerance impact on the design can be changed accordingly, increasing or decreasing design limitations. See Figure 2.13.

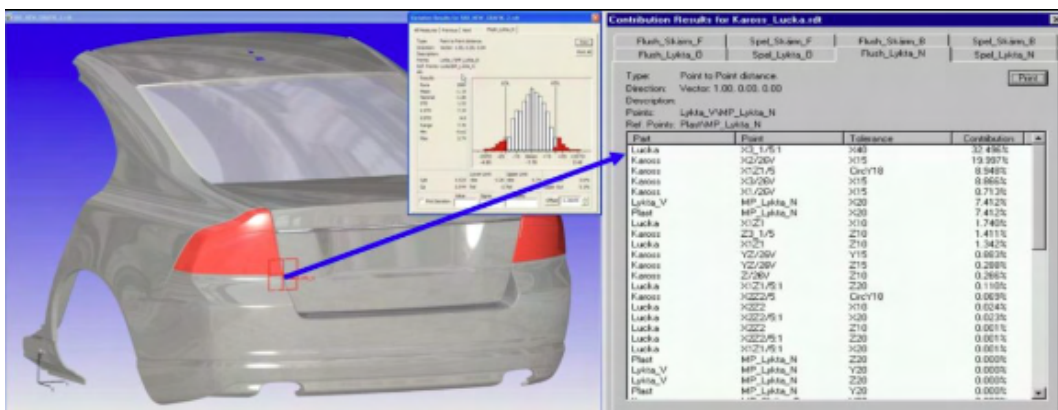


Figure 2.13: Contribution of tolerances in critical measures (RD&T, 2025).

2.5.2 Virtual Fixture

Virtual fixture refers to the process of creating virtual fixtures for part or assemblies in digital softwares like RD&T. This method makes it possible to analyze the parts free state shape with regards to spring-back effect (Lindau et al., 2020). This is not possible in traditional testing as the part usually is over-constrained by several more clamps than its amount of degrees of freedom, effectively bending the part towards its nominal state. Additionally, the traditional way of clamping does not take into account the forces applied from the clamps resulting in a loss of spring-back data after release. Performing a realistic simulation of part contribution to variation in assembly becomes much more difficult because of this. Using virtual fixtures and having an understanding of a part's free state is therefore essential when analyzing non-rigid digital assembly models. An article (Lindau et al., 2020) thoroughly describes the steps necessary to create a realistic digital fixture representation, these being the following:

3D-Scanning of Parts

One of the most prevalent steps is creating a efficient and accessible, ergonomically sustainable 3D-scanning station for the operator that performs the scanning. To establish a standardized way of 3D-scanning the following steps should be conducted.

1. Three adjustable sphere supports rigged on a horizontal measurement base plate so so that part can be positioned and rest close to parallel with clearance from sharp radius's.
2. Position part on the supports.
3. Scan part to acquire resting geometry.
4. Remove part to scan the resting points coordinates as well as small portions of base plate.

This procedure will produce three resulting point-clouds. A point-cloud of the part geometry which describes shape, a point-cloud that describes position of the sphere supports, and a point-cloud which describes the plane perpendicular to the gravity field.

2.5.3 Meshing

To accurately simulate the physical behavior of components in digital environments, meshing is essential. This process involves making a CAD model into a network of interconnected nodes and elements, forming the foundation for FEA. Each node solves equations in relation to each other, predicting deformations, stresses, and displacements under applied loads, such as those induced during assembly or welding.

Different mesh types are used depending on the application:

1. volume meshes (e.g., tetrahedral or hexahedral elements): model thick or solid components and are ideal for plastic components.

2. surface meshes: thin shell or mid-surface meshes are ideal for sheet metal or lightweight structures.

The quality of meshes is crucial in realizing an accurate result. Automated meshing tools like ABAQUS, HyperMesh, and ANSYS Meshing can generate a initial model but manual refinement is often required for intricate features to ensure precision. It is currently not possible to create meshes in RD&T. The meshing process used during the case study later in this project is explained in Appendix F.

3

Methodology

In this chapter the methodology for the conducted project is clarified. The methodology design had an mixed method, which started with a literature study to understand the theory of geometry assurance and important topics within this field. In parallel, a comprehensive data collection was coordinated, with qualitative and quantitative interviews that were performed to get practical knowledge about workers' opinions about possibilities regarding the digitalization of the geometry assurance process. This step was also important to get direct information about the current nominal buck verification process, as the workers at Polestar's manufacturing plant in Chongqing, China, were interviewed. The questions posed in the qualitative and quantitative interviews can be found in Appendix A, Appendix B, Appendix C, and Appendix D. Once enough information had been collected about geometry assurance and the current nominal buck verification process at Polestar, a case study was performed and documented. This process was described as a step-by-step guide in RD&T for virtually verifying part geometries, which can be used by Polestar workers. The scanning process and data processing in PolyWorks, as well as the process of creating meshes, are explained in Appendix E and Appendix F. A comparative analysis was also performed where the digital solution was compared to the current physical process, which gave direct hindsight about the possible outcomes of implementation.

3.1 Methodology Design

The methodology had a mixed design including literature study, interviews, a description of the case study and proposed method, and a comparative analysis. The project therefore had a theoretical approach initially, but during the case study there were many practical elements, such as when the parts were 3D scanned.

3.2 Data Collection

The data collection was based on a literature study and interviews, with both qualitative and quantitative elements.

3.2.1 Literature Study

In the study of the literature, all the information extracted regarding the geometric assurances in manufacturing formed the knowledge base for the project. This

included both theoretical frameworks and definitions within this field, as well as specific technology that can be used to measure part geometries. This was necessary to understand related technologies and concepts, which opened up the possibility to develop a case study. The literature was drawn from websites such as Web of Science, Scopus, Taylor & Francis journals, etc. using keywords such as "digitalization", "geometry", "assurance", "virtual", "tools", "nominal", "buck", among others, and combining these in convenient ways in the search string to find the appropriate material.

3.2.2 RD&T

PE Geometry provides courses for training personnel in software such as RD&T, both internally as well as externally to outside organizations. Their former education programs was therefore used to familiarize the project group with RD&T to understand the various modules, which was necessary before the case study.

3.2.3 Interviews

The interviews contained two parts - qualitative and quantitative interviews. The qualitative interviews were held with industry personnel to gather information regarding certain topics of interest, which will be described below. The quantitative interviews were made to gather a larger amount of data of people's opinions regarding possible virtualizations within the field of geometry assurance. These questions were posed to geometry assurance engineers & specialists, which also is described below.

3.2.3.1 Qualitative Interviews

The qualitative interviews were performed by interviewing a few elected employees from either PE Geometry, Polestar, or an outside organization. In total, eight people were interviewed for the qualitative part. The selection of the interviewees was based on their knowledge regarding the technological, economic, and sustainable aspects of the current nominal buck verification process, as well as knowledge about 3D scanning methods, variation simulations & other digital tools, or general knowledge about the geometry assurance process. The purpose of these interviews were to gather this information directly from industry personnel, which could be useful in the analyses conducted during this project. The results from these interviews were described within different areas of importance, which can be seen in Chapter 4.1. The interviews had a structured nature, with questions specifically constructed for each interview. This is because the interviewees had different roles and specialized knowledge within these fields.

PE Geometry, Gothenburg

The employees at PE Geometry, Gothenburg are experts in the field of geometry assurance and 3D scanning processes, and their knowledge was necessary to extract in order to get hands-on information about current processes. Some of their employees are consultants for Polestar and were also supervisors for this project. Two

people from PE Geometry were interviewed in the qualitative interviews. One being a Geometry Assurance Engineer, consultant for Volvo Trucks, but who was knowledgeable about 3D scanning technology in general. Therefore he was questioned regarding the 3D scanning process, its efficiency, its possibilities to implement the technology in mass production processes, and so on. This information was necessary as 3D scanning of parts was believed to be an important step in a digitalization of the nominal buck verification process. The second person is an employee at PE Geometry as well as consultant for Polestar, with the role as Geometry Assurance Expert, and he is knowledgeable about current geometric analyzing methods and the nominal buck process in Chongqing, China. Questions were asked regarding communication, file handling, different uses of softwares, etc., between the different Polestar departments in China, the United Kingdom, and Sweden. The questions posed to PE Geometry can be found in Appendix A.

Polestar, Chongqing

In order to get insight into the nominal buck verification process, three employees at Polestar's manufacturing plant in Chongqing, China were interviewed. The first one is the Team Leader in geometry assurance and Audit at the plant in Chongqing. He is an expert in the overall verification process, and it was important to extract information regarding his opinions on a possible digitalization of the current process. The second interview was held with the Planner & Leader for nominal buck activities at the plant. He knows information about exact lead times, possible disruptions, advantages and disadvantages of current process. The third interview was held with the Specifier of Manufacturing Requirements for nominal buck & Supplier Contact Person. Questions were asked regarding the costs of manufacturing a nominal buck, manufacturing and delivery times of such a buck, and important aspects connected to this. The questions posed to Polestar can be found in appendix B.

Other people with expertise

Two interviews were held with people are not working at either PE Geometry or Polestar, but who have knowledge about quality verification processes, as well as possible digitalizations. The first interview was held with a Senior Analysis Engineer at Volvo Cars in Gothenburg. They have been part of similar projects in the past, with the objective of digitalizing the geometry verification process at Volvo Cars. This has included scanning physical parts, transferring these geometries to 3D data, and then using that data to perform variation analysis using virtual tools such as RD&T. Therefore this interview was crucial for understanding the possibilities within this field. The second interview was held with two persons - a Deputy Head of Department and Professor at Chalmers University of Technology, as well as a Docent in Product Development at Chalmers University of Technology. Both are conducting their work within the Department of Industrial and Materials. One of them is also the examiner and supervisor for this project. The questions posed to these three people can be found in appendix C.

3.2.3.2 Quantitative Interview

Quantitative research utilizes two tools - experiments or surveys (Smith, 2024). Therefore a quantitative question form was created and sent out to a larger group of people. It was necessary that the respondents either had worked with geometry assurance or had the required knowledge to answer the questions. The question form was used to get people's opinions about geometry assurance and the possibilities of digitalization within this field. The project workers made assumptions about important aspects within the field of geometry assurance, and structured the questions accordingly. Questions were either multiple choice, one choice, or open-ended. The form was sent out to people having roles as Geometry Assurance Engineers, Geometry Assurance Specialists, or similar on LinkedIn, where their job titles could be acknowledged directly. The questions posed in this question form can be found in appendix D.

3.3 Case Study

Once the literature study and interviews had been performed, a specific digital method was developed further and demonstrated in a case study. This case study was continuously constructed during the project, and much of the information regarding certain steps was brought from PE Geometry's internal courses regarding the work procedure in RD&T. Simultaneously, discussions were conducted with industry personnel at PE Geometry to understand the crucial steps in reaching a final solution which has not been described in this report. The first step of a digital geometry assurance process is transforming the physical part to a digital 3D model, which is done with help of scanning equipment. The technology of 3D scanning is explained in chapter 2.4.1. There exist different scanning methods for doing this transformation. Once the part's geometry has been transformed to a digital file, it can be implemented in the RD&T software and used for simulation purposes. Meshes of CAD data also needed to be created for all parts involved in the final assembly.

The case focused on non-rigid variation analysis of a sub-assembly and showed the steps necessary to compare nominal parts to actual produced parts. This was done to create a standardized way to perform virtual geometry assurance and showcase the advantages of using software like RD&T. The area chosen to be simulated in the case study was the B-pillar with belonging components, specifically the intermediate and lower parts of the left-hand interior design. The parts in question were of plastic material and were chosen because of their critical position in the assembly. This area is composed of several meeting points of different parts, making it a prime investigation target. Consequently, proving that simulation is possible in this area entails it is most likely possible to simulate any section of the car.

3.3.1 Step-by-Step Guide for RD&T, Meshing, PolyWorks, and Scanning Process

In parallel with performing the case study, the process was documented and explained in the report as a step-by-step guide. The idea is that the guide can be used by Polestar workers to digitally verify parts using RD&T. The main objective of this guide was therefore to explain all necessary steps in RD&T. As PolyWorks must be used to gather and process the scan data, a step-by-step guide of this step was explained in a similar manner in Appendix E, which also contains a description of the practical scanning procedure. Likewise, as meshing was a necessary step to reach the final results, which was not performed in RD&T, the process for this was explained in Appendix F. The meshes were created in the HyperMesh software.

3.4 Comparative Analysis - Physical and Digital Verification Methods

To gain an understanding of the aspects that both the physical and a possible virtual method would incur, a comparative analysis was constructed. The current physical process was compared to the alternative virtual approach and advantages and disadvantages was analyzed. This was done by analyzing important areas such as efficiency, accuracy, cost, sustainability, and flexibility, to showcase directly what advantages and disadvantages Polestar will face when implementing virtual tools in their geometry assurance process.

Furthermore, the implementation feasibility includes a completely new virtual workflow process based on the conclusions of the results.

3.5 Impact of Virtual Implementation

Another section focuses on describing what the direct effects for Polestar if they decide to implement the proposed digital method. Data for this analysis is based on information from the industry interviews and case study, as well as internal information from Polestar. This discussion also includes a completely new virtual workflow process based on the conclusions of the results, where some areas of the previous workflow could be completely eliminated. A subchapter will also entail the implementation feasibility of the digital method for an organization such as Polestar, as well as the possibilities to automate many steps of the digital method to make it fit in a large-scale use.

4

Result

This chapter presents the results obtained from the key stages of the methodology. These include findings from both the qualitative and quantitative interviews, the development of a step-by-step case study guide, a comparative analysis of the physical and virtual nominal buck, and an evaluation of the impact of virtual implementation.

4.1 Findings from Industry Interviews

Interviews with key personnel at the factory in Chongqing, China as well as an Polestar Geometry Assurance Expert include:

- Team Leader and Audit Expert in Chongqing, China (Appendix B)
- Planner and Nominal Buck Leader in Chongqing, China (Appendix B)
- Specifier and Supplier Contact in Chongqing, China (Appendix B)
- Geometry Assurance Expert & Geometry Program Manager in Gothenburg (Appendix A)

These interviews provided valuable insights into the physical nominal buck process as a whole and information regarding communication & collaboration between the different international departments at Polestar.

4.1.1 Current Physical Nominal Buck Process

In the initial stage, the factory team, consisting of 30-40 R&D engineers, 5 geometry engineers, and 4 measuring technicians begin by freezing the nominal buck design data. This means that no further modifications are allowed at this stage. The team then works together with the supplier to review the nominal buck design. This stage is vital to ensure the design can be manufactured, easily assembled and disassembled efficiently. From first data freeze to ready-to-manufacture model usually takes about three months.

Once the ready-to-manufacture model has been obtained the suppliers can start the manufacturing. To review the suppliers process and validate results, the whole factory team visit the supplier. If something is not up to standard at this point, this is notified and the supplier will need to change their process. Finally, when all details of the nominal buck is satisfactory, a final acceptance check is performed before the nominal buck is shipped to the plant. The complete nominal buck creation process

can be seen in Figure 4.1.

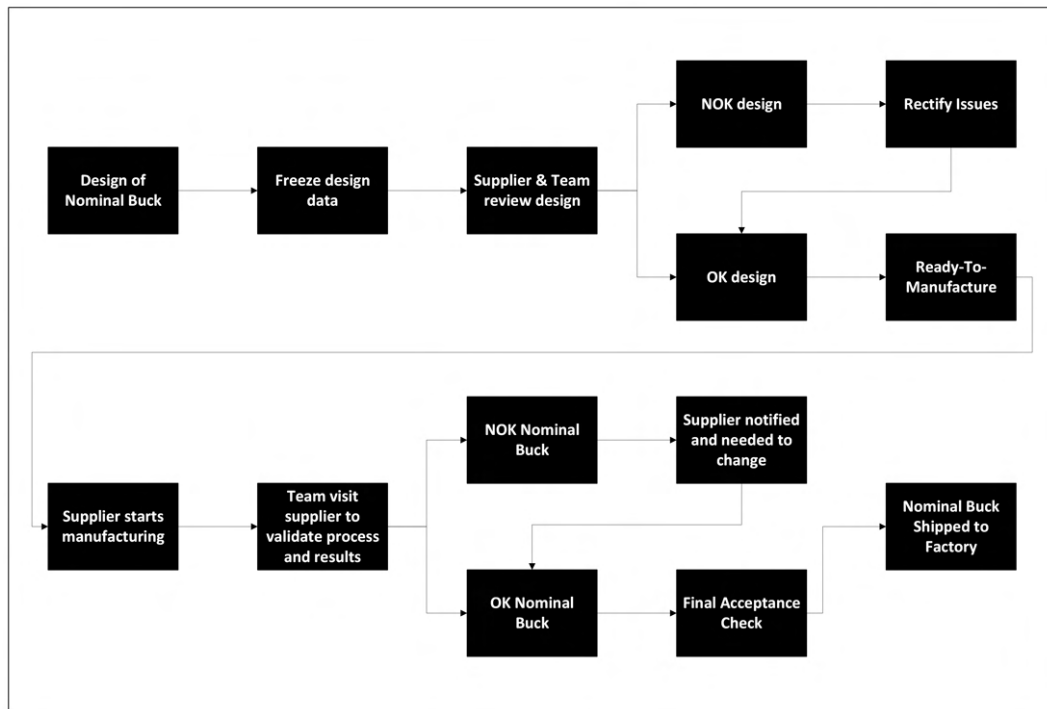


Figure 4.1: Nominal buck creation process.

At the factory, the nominal buck serves as a reference structure for testing and evaluating the fit of both exterior and interior components. To support this, a variety of physical fixtures are utilized. These fixtures are custom-designed and manufactured alongside the buck to mimic the attachment interfaces found in the actual vehicle assembly. They consist of rigid metallic brackets, support frames, and locator pins that hold parts in place in a repeatable, predefined orientation.

Fixtures play a critical role in ensuring consistency during measurement and visual evaluation. They enable engineers to mount components with the same geometry and constraints as in the real car. This allows for precise verification of gap and flush conditions, alignment, and fitment. The use of fixtures also helps minimize part movement during probing and 3D scanning operations, ensuring accurate and repeatable results. In addition to their use during part fitment, fixtures often include built-in reference points that interface with Coordinate Measuring Machines (CMMs), simplifying the process of data acquisition. When small design modifications are made, these fixtures can be re-machined to accommodate updated geometries.

When the nominal buck has arrived at the factory, testing and measuring can begin. As mentioned in earlier chapters, the nominal buck is used to check the fit of exterior and interior parts. Measurements here are mostly done using a probe mounted CMM but 3D-scanning is also possible. If there is a part with irregular

shape, special gauges are used to measure gap and flush measures between parts. These measurements are then documented in measurement reports. During the measurement and testing process, the sample size of each batch is different depending on earlier experiences. For example, if part has been outside tolerances earlier, 25-50 parts are measured to ensure validity of quality. On the other hand, if the part has been without issue earlier, only around 10 parts need to be measured. For each build phase of the car, the measurement process is performed two times to ensure accuracy. If there are deviations from the specifications, these are documented in a software called PIRA.

If enough parts are out of specification, the batch is sent back to the supplier. The supplier is then notified by the team what is wrong with the batch and required to remanufacture the batch to create a better standard. If the problem is not with the suppliers product but with how parts fit together in the assembly, design changes of the nominal buck can sometimes be necessary. Modifications are usually divided into minor and major changes. Minor changes are problems which can be fixed on site in a couple of days, for example, grinding or polishing. Major changes involve needing to change the very geometry of the nominal buck itself. This entails that the nominal buck will need to be sent back to the manufacturer where it is re-manufactured. These changes can take anywhere from one to three months. To visualize the part verification process in the nominal buck, a flowchart is displayed in Figure 4.2 below.

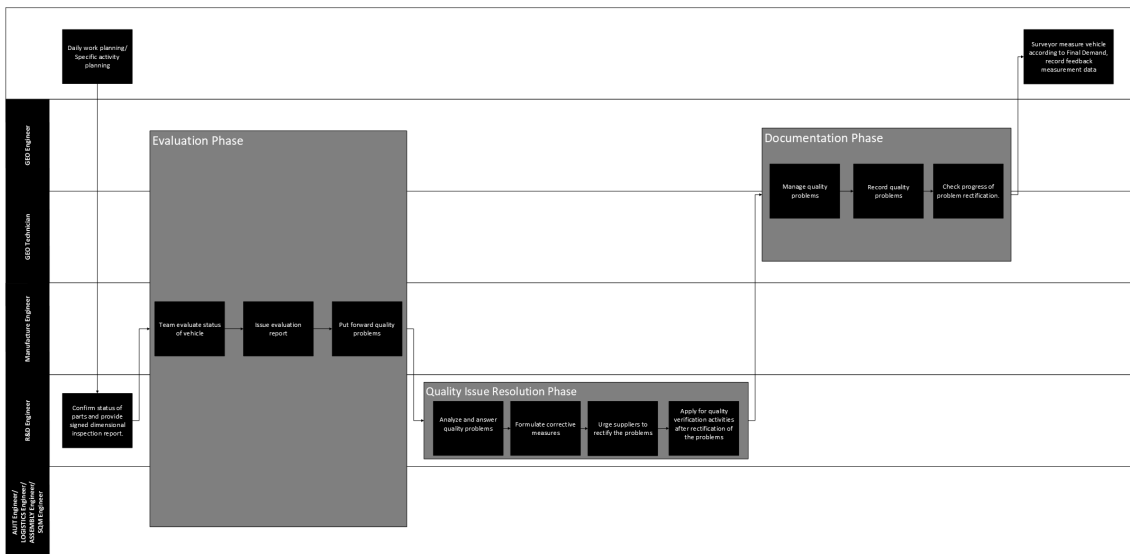


Figure 4.2: Physical part verification process in nominal buck.

Challenges of Physical Verification Process

Along with the physical process several challenges, both logistical or geometrical, arise. This chapter aims to pinpoint mentioned challenges and explain their origin.

Measurements of details in the nominal buck is a time-consuming process. First of all, engineers need to measure parts, then the engineers need to assemble the parts

on the nominal buck. After this step, they need to disassemble the parts. This process needs to be done for all the interior and exterior parts of the car. Furthermore, as mentioned in the earlier chapter, this is done anywhere from 10-50 times per part, two times per build phase, doubling the time spent for the activity. This can pose significant problems for the project time-frame if not conducted efficiently.

Design changes are required based on the robustness of individual parts and the nominal buck as a whole. Typically, several adjustments are needed. These modifications take place after data is frozen and the design is re-evaluated. Chapter 4.1.1 discusses minor changes, which can be made onsite within a few days, and major changes, which involve shipping the nominal buck back to the supplier, a process that can take anywhere from one to three months. When working on a tight schedule, as is the case with automotive manufacturing, these design changes result in delayed development times.

In the initial production stage, known as PS, suppliers submit measurement reports to the factory team in China. However, these reports do not guarantee that the parts are within tolerances. As a result, the team cannot be certain whether a part will properly fit the nominal buck. The final judgment is made visually by the team once the part is placed on the nominal buck, relying on prior experience. Furthermore, there is no virtual verification system to check parts before shipment. These two factors significantly increase the risk of wasted time and resources.

While the cost of a nominal buck is not a major problem for a company like Polestar, it can still impact the company negatively. Currently, the nominal buck cost varies depending on supplier and what is asked of the supplier. For example, in China, a nominal buck for an SUV that includes 100% of the exterior and 20% of the interior parts costs around 4 million RMB, which is roughly 5.4 million SEK. Seen in Figure 4.3 is the budget for Polestar 5 Nominal buck and fixtures as well as actual money spent on them accordingly. Note that the prices are in units of 10 000 RMB. The money spent on the nominal buck and fixtures total 3,51 million RMB, or 4.78 million SEK. Note this is only for money spent on manufacturing the fixtures and nominal buck, not total money spent on development.

专业	项目 Items	预算 Budget	合同价格 Contract price
尺寸GEO	Holding fixture	90.0	72.00
尺寸GEO	Nominal buck	360.0	279.00

Figure 4.3: Budget for the nominal buck. Costs are in units of 10 000 RMB. 351 = 3 510 000 RMB.

Another challenge worth noting are the ergonomical difficulties. When workers have to fit parts onto the nominal buck, certain motions like bending and reaching can be stressful for the body. Even though this is not a major problem in the physical process, it is something that would be better of eliminated.

Communication Regarding Nominal Buck

Communication regarding geometry assurance processes is transferred between the R&D department in the United Kingdom, the Manufacturing Engineering (ME) department in Gothenburg, as well as the manufacturing plant in Chongqing, China. It is of importance to ensure that design requirements are properly understood among the teams, and evaluated and implemented within manufacturing while filtering and prioritizing relevant changes to minimize disruptions.

Communication with the Chinese plant is structured around project-related meetings, with tasks varying depending on the project's stage. Regular weekly meetings allow for information sharing, while direct communication between R&D and the production team is encouraged to reduce unnecessary intermediaries. Over time, a strong level of trust has been established between departments, allowing for more streamlined interactions. A similar approach is taken with the UK-based teams, where collaboration is frequent but not bound by fixed meeting schedules. Instead, tasks dictate interactions, and the flexibility in communication has helped foster strong relationships.

Challenges of Communication

Information transfer regarding design changes are often efficient and smooth, but can be challenging, particularly if not communicated at the right time. Small adjustments, such as hole repositioning, are relatively easy to implement, whereas larger modifications affecting surfaces or pressing tools require significantly more effort and time. Ensuring timely information flow is therefore critical to minimizing delays in production adjustments.

One notable challenge in global communication is language. Despite a strong command of English within teams, differences in terminology can lead to misunderstandings, even among native Swedish speakers. These challenges are amplified when communicating across Swedish, English, and Chinese teams. Additionally, time zone differences restrict available meeting times, limiting the overlap for direct collaboration with the Chinese plant to a few hours per day.

From a software perspective, the daily workflow involves a variety of tools, including PowerPoint, Teams, and TCVis. While RD&T is used to generate key measurement data, the Chinese team integrates this information into their own applications, such as the Final Demand App, which provides structured measurement instructions. Data transformation between RD&T and other formats is crucial in this process, but conversion errors have occasionally led to misinterpretations—for instance, a flush condition that should be -4 appearing as +4 after conversion.

The interview also highlighted the importance of clearly defining roles and responsibilities. Differences in organizational structures between Polestar and its former parent company, Volvo Cars, have created challenges in aligning workflows. Historically, teams have relied on legacy processes from Volvo, but variations in company structures require clarification of roles to avoid inefficiencies and duplicated efforts.

Currently, steps are being taken to establish clearer role definitions to enhance operational efficiency.

4.1.2 3D Scanning Technology

Information regarding 3D scanning technology was extracted from the following interviews:

- Geometry Assurance Engineer at PE Geometry, Consultant for Volvo Trucks (Appendix A)

One of the key advantages of 3D scanning in geometry assurance is its ability to collect large amounts of measurement data, enabling comprehensive analysis and historical comparisons. Unlike traditional methods, 3D scanning is non-contact, meaning it does not interfere with the setup, making it possible to capture measurements step-by-step during assembly. Additionally, scanned parts can be virtually assembled & disassembled in simulation software, allowing engineers to predict potential issues before physical production begins. Some factories have also started implementing automation, where real-time scanning is used to align components such as windshields during the assembly process.

The large volume of data generated from frequent scans can be difficult to manage and store efficiently. Scanning software also applies filtering algorithms that smooth surfaces, potentially masking minor but critical deviations. Accuracy can be affected by extreme angles or the positioning of the scanning arm, leading to misalignment in measurement results. Additionally, ensuring trust in the system is essential, as understanding how the software processes and filters data is crucial for achieving reliable results.

Some conclusions can be drawn regarding advantages of the 3D scanning technology in geometry assurance settings. These include:

- **Increased data collection:** Allows for comprehensive analysis and historical comparisons.
- **Non-contact measurement:** Enables scanning without disturbing the setup, allowing for step-by-step analysis of assembled components.
- **Virtual assembly testing:** Scanned parts can be virtually assembled to predict outcomes before physical production.
- **Automation potential:** Some factories already use automated scanning, such as aligning windshields based on real-time scan data.

There are also some challenges & limitations that can be associated with 3D scanning technologies. These include:

- **Data volume:** Large datasets from frequent scans can be difficult to manage and store.

- **Software filtering:** Scanning software smooths surfaces, potentially considering deviations as noise and therefore inaccurately filtering them out.
- **Accuracy concerns:** Misalignment can occur due to extreme angles or positioning of the scanning arm.
- **System trust:** Understanding how the software processes and filters data is crucial for reliable results.

4.1.3 Virtual Initiatives at External Organizations

One interview yielded information regarding past virtual initiatives at external companies, organizations, and projects. The information was valuable to get a more comprehensive understanding of the possibilities and limitations of such technologies in manufacturing settings. The following interviews were used for this purpose:

- Senior Analysis Engineer at Volvo Cars (Appendix C)

Over the past years, significant advancements have been made in virtualizing geometry assurance processes at Volvo Cars, particularly in virtual simulations. The primary focus has been on compliant simulations rather than traditional tolerance chains. However, due to recent company restructuring, the prioritization of virtual geometry assurance has decreased, leading to a reduction in dedicated personnel and a redirection of expertise to other areas deemed more critical to the organization's overall strategy. While virtualization efforts continue, the full potential of these technologies has yet to be fully realized.

For variation simulations, Volvo Cars primarily uses RD&T, complemented by other commercial software for specific structural simulations. The idea of virtual fixtures, described in chapter 2.5.2, was developed by the interviewee and their colleague at Volvo Cars. Virtual fixtures are not yet used in real manufacturing settings at Volvo Cars, but it is a long-term goal for the company to implement the technology. Additionally, 3D scanning plays a crucial role in virtual verification, with handheld arm scanners used to capture free state (a concept which is explained in chapter 2.5.2) scans of components. These scans are typically performed by suppliers, who provide STL files that are integrated into simulation models. The virtual verification process is closely aligned with the vehicle development timeline, beginning in the pre-series and prototyping phase. Before physical assembly starts, suppliers scan parts and submit the data to Volvo Cars, which then can use the data in their simulation software.

Challenges of Virtual Implementations

Across the industry, a common challenge is the lack of management prioritization for virtual verification, preventing it from becoming a standardized practice. There are cases when companies have made significant progress in virtual assurance by developing tools, methodologies, and supplier requirements to improve geometry assurance. However, when this area is no longer seen as a strategic priority, resources

are redirected, often resulting in limited personnel to drive virtual advancements. This deprioritization slows technological progress and may explain why virtual geometry assurance has not yet been fully implemented as a standard practice in many organizations.

Cultural and technological resistance exists within production teams, where traditional physical verification methods are more deeply ingrained. While R&D departments frequently rely on simulations for structural validation, manufacturing teams have been slower to integrate virtual simulations into their decision-making processes.

A major challenge in virtual geometry assurance is the inconsistency of scan data provided by suppliers. The quality of these scans varies, often due to differences in measurement equipment, scanning techniques, or calibration standards. This inconsistency affects the reliability of the data used for simulations, leading to discrepancies between virtual models and physical parts. A specific issue is the alignment of holes and slots, which are critical for assembly accuracy. If these features are misaligned in the scan data, simulations may produce misleading results, impacting decision-making and problem-solving. Without standardized scanning procedures across suppliers, additional verification steps are required, increasing workload and reducing efficiency.

4.1.4 Research Within Virtual Geometry Assurance

Interviews with academic researchers, mentioned below, specializing in virtual geometry assurance provided valuable insight into current and future aspects of the area:

- Deputy Head of Industrial and Materials Science Department, Chalmers University of Technology (Appendix C)
- Associate Professor of Industrial and Materials Science, Chalmers University of Technology (Appendix C)

Both interviewees are experts in virtual geometry assurance with decades of experience in academia and industry (including Volvo Cars and Saab Automotive). Their work has focused on increasing accuracy and efficiency of simulations to reduce reliance on physical prototypes. Currently their research focus on removing limitations of simulation tools such as:

- Creating accurate simulation tools for simulating factors like continuous welding deformations.
- Reducing computational time through optimization techniques.

There are many advantages of using virtual geometry assurance within automotive manufacturing. Some of the key mentions include:

Advantages of Virtual Geometry Assurance

One of the biggest benefits of virtual geometry assurance is its ability to identify and resolve design issues in early design stages such as the concept, prototyping or pre-production phases. By simulating car models virtually before actual production is started, the time needed for part verification can be significantly decreased. Furthermore, multiple design iterations of a design can be quickly evaluated without the need for manufacturing, saving time, money and manpower. Another great aspect is that it enables closer collaboration between teams. Providing a virtual platform where the design is shared and can be modified in real time by design, manufacturing and quality assurance teams at the same time makes the process easier and faster.

Virtual geometry assurance enables companies to significantly cut costs. Since parts are tested in a virtual environment, there is no need to manufacture the parts for testing. However, physical parts will still be needed toward the end of the verification process to visualize and test the final assembly of the car. Until that point, parts to test requirements and visual aesthetics will not be needed, significantly reducing cost of the process. Additionally, this ties into the sustainability of the company as well. By limiting material usage the waste produced in each production phase is decreased, making the process more sustainable as a whole.

Since virtual geometry assurance allows for thousands of variation simulations to be run simultaneously, the amount of measurements can be greatly increased. This, in combination with real-world scanned data of manufactured parts can effectively predict deviations from the tolerances set. These factors save both time and manpower.

Challenges of Virtual Geometry Assurance

One of the biggest challenges of virtual geometry assurance is the trade-off between simulation accuracy and computational efficiency. Including more physical phenomenons such as welding deformation, heat effect or spring-back information improves accuracy but makes simulations more time-consuming. As such, approximate methods to calculate head effect is often used, resulting in a loss of accuracy. Also, when analyzing models with more details, finer meshes are required, increasing memory usage and computation time.

When conducting non-rigid simulations of parts, scans of the parts are required. This is done to acquire the free-form state of the part to get a as realistic simulation as possible in regard to spring back effect, mentioned earlier in chapter 2.5.2. The point cloud data extracted from scanning is extremely large and contain millions of data points. If this data is not optimized, performing simulations with multiple parts can overwhelm computing power. Because of this, engineers responsible need to filter and process the data so that only necessary geometric features are simulated.

Also, similarly to 4.1.3, organizational resistance to change is one of the main obstacles to implementing simulation tools like RD&T. Many organizations face skepticism and reluctance when adopting new technologies due to comfort with existing practices, fear of disruption, and perceived complexity. Employees may resist due

to a lack of understanding or fear of failure, while management might be concerned about the potential challenges of integrating new tools into current systems and related costs.

Overcoming this resistance requires clear communication of the benefits, involvement of key stakeholders early on, and tailored training programs. Leaders should foster a culture of continuous improvement and provide ongoing support to ensure smooth integration and build confidence in the new tool. By addressing these challenges, organizations can successfully implement RD&T and unlock significant benefits in efficiency and decision-making.

4.2 Quantitative Interview Findings

The quantitative question form was sent out to 53 individuals and a total of 15 individuals answered the form. The form was specifically sent out to people working with geometry assurance, thus each individual is a specialist on the subject and has their own views and opinions about the virtualization possibilities within this field. Another word for geometry assurance is geometry verification, and as the term geometry assurance is quite uncommon in other industries than automotive, many questions are posed with the term geometry verification. However these two concepts are the same and can therefore be used interchangeably. As can be seen in Figure 4.4, the participants came from different sectors of work which gave valuable insight within these industries. The most common sector of work was automotive, which is expected as the subject of geometry assurance is especially common and important within this industry.

Within which sector do your company operate?

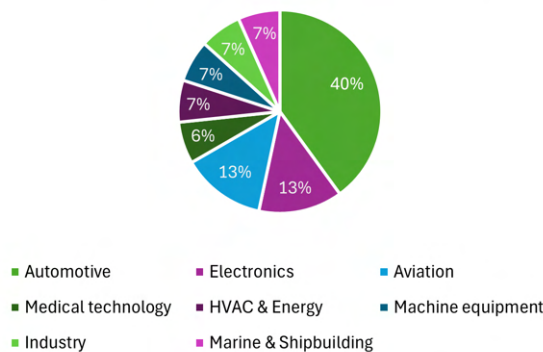


Figure 4.4: The circle shows that the interviewees came from various industries.

Two other questions were posed regarding the participants familiarity with virtual geometry assurance processes, and whether their processes are currently conducted physically or virtually within their respective company. The results can be seen in Figure 4.5. As can be seen, 80% are using a mix of both physical and virtual

verification methods.

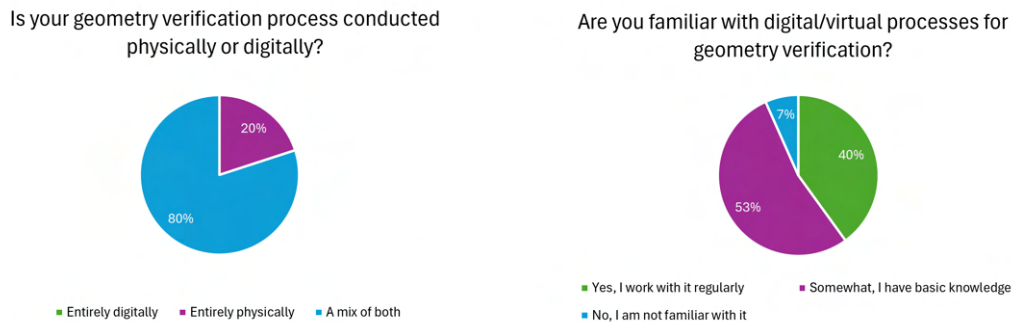


Figure 4.5: How the correspondents perform geometry assurance and their familiarity with virtual tools.

A question was also posed regarding specific software that the various interviewees are using when performing analyses and calculations. The list below demonstrate which software that the respondents use during geometry assurance processes:

- RD&T
- Creo View
- 3DCS
- LK Camio
- Polyworks
- ATS CM4D
- Crystal Ball

The most common software for geometry assurance seems to be RD&T based on the results. Another aspect of interest was the effectiveness of geometry assurance processes at the different companies. Therefore the subjects were able to rate their company's geometry assurance process from 1 to 10, where 1 represents not effective and 10 represents very effective. The participants were also posed a question regarding how willing they were to virtualize their geometry verification process, from 1 to 10, where 1 represents not willing and 10 represents very willing. The results of these questions can be seen in Figure 4.6. As can be seen, some participants rate their current geometry verification process as quite mediocre in their effectiveness, while they rate highly on their willingness to virtualize the process. This shows that there is a common need for virtual technologies in geometry assurance across many industries.

4. Result

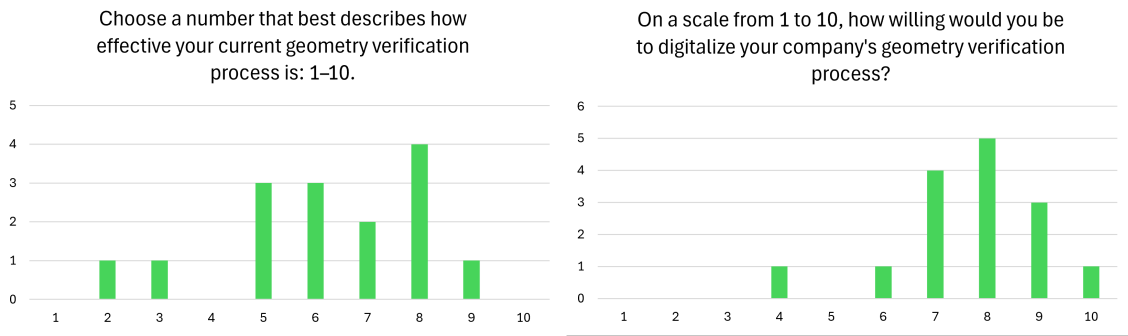


Figure 4.6: The effectiveness of current geometry verification processes at each individual's company, as well as their willingness to virtualize geometry verification processes.

Furthermore, a question was posed regarding if the participants believed a virtualization of their process would be beneficial to the company, with a majority voting yes. Another question was also asked regarding if the individuals and the companies they represent have implemented virtual tools, and in which stage they are. Here the results were quite even, showing that some companies have put more resources into virtualizing their geometry assurance processes, while others are only planning it so far. The results of these questions can be seen in 4.7.



Figure 4.7: Questions regarding if the participants deemed a virtualization of the geometry assurance process to be beneficial, as well as how far they have come in implementing virtual tools.

Furthermore, it was of importance to get an idea of what kind of obstacles people may perceive when it comes to virtualizing geometry assurance processes, as well as opinions about sustainability aspects. A question was therefore posed regarding this which can be seen in Figure 4.8. The reason why this is of interest is because it may give an idea of what kind of barriers one must overcome in order to successfully virtualize within this field. It is not a straightforward concept yet. As can be seen, high cost and lack of knowledge & expertise seem to be the most prevalent barriers according to the responses. Another great barrier is the resistance of change within company, a common problem among many companies when discussing virtualization.

4. Result

What do you think is the biggest barrier to digitalizing your company's geometry verification process?

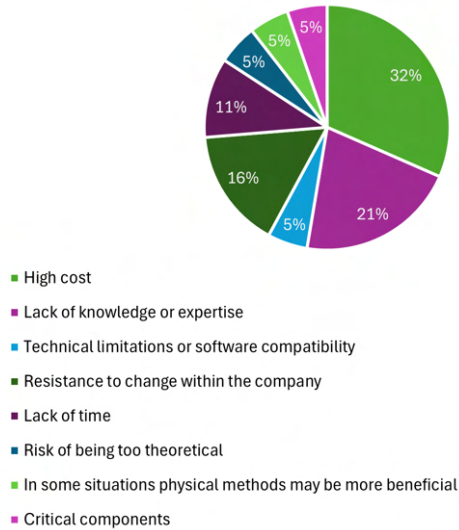
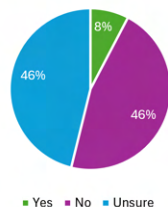


Figure 4.8: Opinions regarding various barriers the respondents may perceive when planning to virtualize geometry assurance processes.

Two other questions were posed regarding sustainability aspects (see Figure 4.9). The first one asked if the participants believed their geometry verification process is ergonomically demanding. In this diagram, the results are even. Half of the respondents think the verification process is ergonomically demanding, the other half do not think there is a problem. This may depend on what kind of sector they work in. Some sectors, such as the automotive industry, need to handle quite large parts, which definitely could pose an ergonomic problem for the operators. Secondly, a question was posed regarding if the respondents believed that virtual tools lead to reduced waste. The majority with 67% answered that they believed there would be a slight decrease, and 20% believed there would be a significant decrease.

Do you think your physical verification process is ergonomically demanding? (If you verify digitally, please skip this question)



Do you think digital verification methods lead to reduced waste (compared to a physical method)?

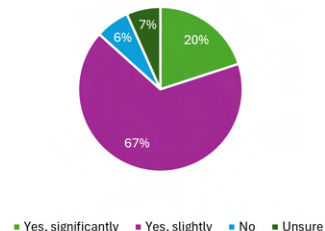


Figure 4.9: Opinions regarding ergonomic aspect of current processes, and potential waste reduction when virtualizing.

The final question asked the participants what they believed would be the major

sustainability benefits when virtualizing (see Figure 4.10). As can be seen, reduced costs and increased efficiency seems to be the major benefits.

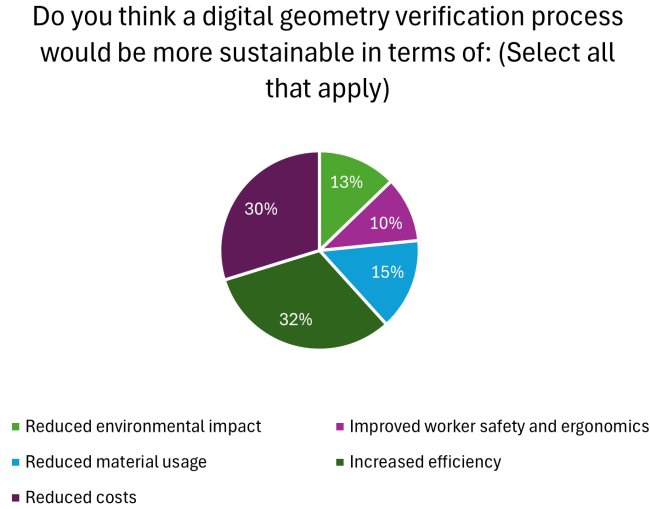


Figure 4.10: Opinions regarding the improvements within sustainability when digitalizing.

4.3 Case Study

To demonstrate how Polestar’s geometry verification process could be performed virtually, a case study will be created. Chapter 4.3.1 aims to create a methodology which is feasible for Polestar in their production settings to enable a virtual verification of the nominal buck. This part aims to depict key software and methods that can be used to perform the simulations to get the most accurate results. The next chapter 4.3.2 is a step-by-step explanation of how to create the RD&T model to perform the simulations.

4.3.1 Virtual Verification Methodology

First of all, as mentioned in earlier chapters, the software chosen to create simulations is limited to RD&T. It is worth mentioning that there are several other Robust Design and Tolerancing softwares on the market which could be used but since this thesis was done in collaboration with Polestar and PE geometry, RD&T was the provided software. Furthermore, RD&T is developed by researchers at Wingquist laboratory, an internationally competitive competence centre for multidisciplinary research within the field of virtual product realization. In collaboration with Volvo Group, they develop new virtual tools to simulate scenarios putting them at the forefront of automotive geometry assurance research. This solidifies RD&T as an expert tool to perform the simulations at hand.

Meshing of Parts

The first step is to mesh all appropriate CAD models. This is not done in RD&T but in a arbitrary meshing software, thus it will not be included in chapter 4.3.2 which describes the RD&T process. However, a description of the meshing procedure can be found in Appendix F. Depending on part material, thickness and geometry, a surface mesh or solid mesh is preferred. These are fundamentally different, solid meshes are 3D volume meshes of a parts entire geometry while surface meshes are 2D meshes of the parts surface. For this project, surface meshes of specific part's mid-surface are used. Additionally, depending on which mesh is used, it can be harder to simulate in RD&T. For example, as stated by the researchers in chapter 4.1.4, solid meshes take more computing power since the whole 3D object is meshed with nodes throughout. Furthermore, meshing parts with complicated geometries such as ribs can pose problems as the mesh may require significant refinement to accurately capture intricate details. This refinement often leads to an increase in the number of elements, which in turn escalates computational demands and simulation time. The mesh is necessary to discretize the CAD geometry into small elements that can be used to solve the equations of the case being simulated, such as stress or heat transfer. Something else worth noting is a finer mesh can capture more detailed results though it requires more computational power and time. On the other hand, a coarser reduce need for computational power but could result in missing important details in the simulation. Without a proper mesh, the simulation software would be unable to accurately represent the complex geometries and material behaviors of the physical part.

Virtual Fixturing & 3D Scanning

To capture the most realistic geometry of the part, virtual fixturing and 3D scanning should be used. These generate several different point-clouds such as surface and boundary scan of the part with realistic deviations. They will later be used to alter and visualize the difference between nominal and scanned part in the simulation.

The preparatory phase of virtual fixturing should be carried out first. In this step, the setup of the 3D scanning phase should be planned. This involves using the virtual fixturing tool in RD&T to virtually position the spheres as efficiently as possible on the part in question. Positioning of the part on the spheres should minimize potential distortions and ensure stability during scanning. Selecting the correct contact points is important to reduce unwanted movement or misalignment. If the part has any distortions after positioning, support points can be added in addition to the spheres to support the model. A more detailed explanation of the Virtual Fixturing process can be found in Chapter 2.5.2.

The 3D scanning process captures the physical geometry of the part and generates a collection of data points that represent the surface of the part. The point cloud captures the most intricate details and deviations from the original CAD model as a cause of manufacturing. Using 3D scanning ensures that the simulation model accurately reflects the physical part, which is critical for validating real-world performance and identifying potential issues that may not be obvious in the nominal

CAD model. Furthermore, 3D scanning can be particularly valuable for reverse engineering applications, where the original design specifications are unavailable or need to be updated based on the as-built condition of the part. The 3D-scanned point-cloud file together with the mesh that was acquired earlier is then used in the virtual fixturing module within RD&T to perform black-box simulations.

Creating a Superpart

When the 3D scanning is complete it is time to create a accurate simulation model. The initial step, which was the meshing of parts, generated the necessary meshes. In the nominal buck, parts are tested against a nominal environment. In this step, that nominal environment is created. This is called a "Superpart". It is a assembly which contain all the meshes that are included in the nominal environment. The first step is to import all meshes into RD&T separately. Then, creating a new part, preferably named "Superpart" or "Assembly" is advised. In the compliant tab of the new superpart the meshes are included to define it as the same part. Weld points are then created between the meshes to assemble them, these being positioned according to the 3D PMI of parts. This affectively mimics one whole part. When this is complete, a positioning system should be created to fixate the superpart in space against a fixture, preferably according to the 3D PMI data as well. By altering the properties in the superpart's compliant tab such as elastic modulus and thickness, the desired material can then be imitated.

Compliant Simulation

Once the scan data has been obtained and imported to RD&T, a compliant simulation can be performed to analyze the part. Compliant simulation need to be utilized since both plastic and sheet metal parts can be deformed in their fixtures or as a result of being mounted by clips. This allow parts to be deformed during simulation and then visualize the result. By specifying certain parts as rigid, done in the previous step, and other as non-rigid as is in reality, the parts will deform as they would in real life. This ensures engineers working with the virtual nominal buck can directly see the end result of forces on the part which is crucial. To start of, the meshes which are going to be analysed need to be imported and positioned. The parts then need to be welded onto the superpart to show its relation to each other. Alternatively, using the clip function depending on how the parts are assembled in reality is a possibility. The parts properties should also be altered to correspond to each parts data sheets. Then the point-cloud from the 3D scanning needs to be imported. This is done using the virtual assembly toolbar in RD&T. After its importation, the deviation of the scanned part to the nominal part can be analyzed. Furthermore, contact searches can be conducted at this stage. This analysis searches for potential clashes between included parts, giving an idea of where tolerances are too wide. This contact search is based on either nominal to nominal or nominal to scanned meshes. At this point, measures such as gap and flush, can be defined between parts included. Performing a variation analysis now will show the distance between scanned parts and nominal meshes. When this is complete, the end result of how to create a realistic virtual representation of the nominal buck is complete.

4.3.2 Virtual Verification Using RD&T

This chapter serves as a step-by-step description of all steps required to perform a virtual geometry verification process using RD&T. This is explained from the perspective of how the case study was performed. Each necessary file and type of data will be explained in the beginning of each step/subchapter, as well as the output of files and data at the end of it.

4.3.2.1 Summary of Steps and Necessary Files & Data

In the following chapter is a summary of all the steps involved in the digital verification method using RD&T. Figure 4.11 demonstrates the different steps in a summary, as well as necessary input of and output of files for each step.

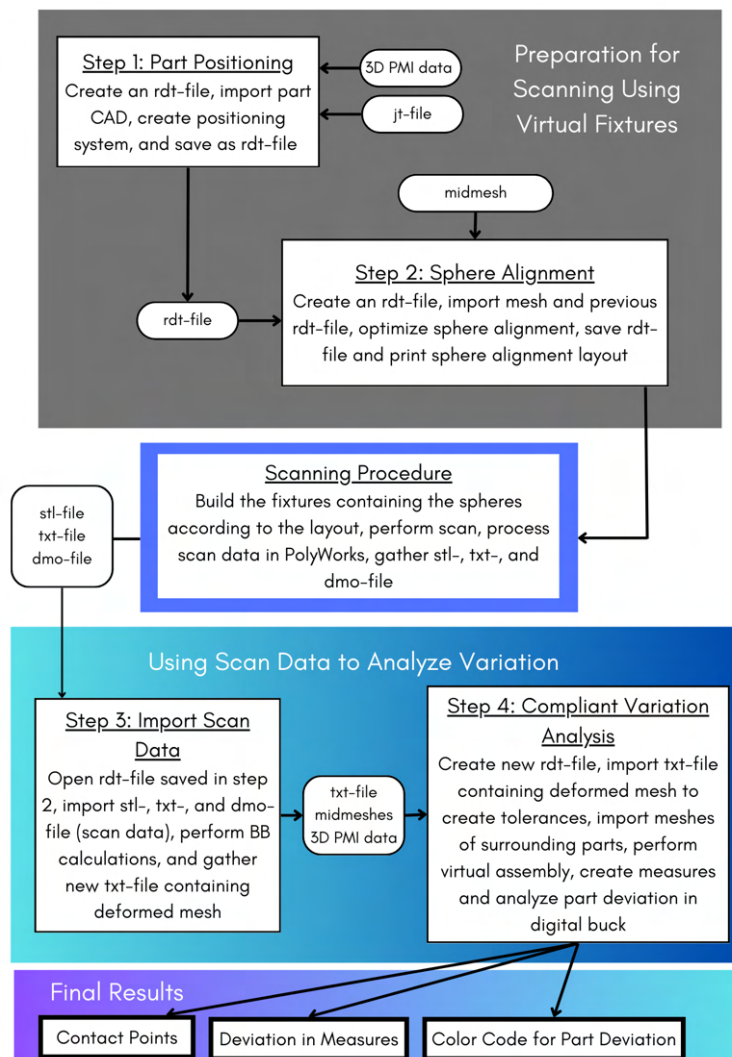


Figure 4.11: A summary of the proposed digital method for the nominal buck verification process using RD&T.

If the objective is to scan and analyze one part, the following amount of files and data are needed in total. The amount of files necessary is also dependent on how

many parts that the analyzed part is assembled to in a vehicle.

- 1 set of 3D PMI data
 - Used to position the part that is to be analyzed
- 3 rdt-files
 - One rdt-file containing the jt-file and positioning system
 - One rdt-file containing the sphere alignment setup, the same file is also used to import scan data and perform the Black Box (BB) calculations
 - One rdt-file to perform the virtual assembly and see the final analysis of part variation
- 1 jt-file
 - The nominal CAD of the part that is to be analyzed
- 1 + x nominal midsurface meshes
 - 1 stands for the part that is to be analyzed
 - x stands for all other parts that the analyzed part is directly assembled to in a vehicle
- 1 dmo-file
 - Contains features of the part which have been extracted from PolyWorks
- 1 stl-file
 - Contains the scan data and is extracted from PolyWorks
- 2 txt-files
 - One txt-file containing the boundary scan, which is exported from PolyWorks after the scanning procedure
 - One txt-file containing the deformed mesh after the BB calculations

4.3.2.2 Step 1: Virtual Fixture - Import CAD and create positioning system

The first step involves preparing the part for the scanning process which will make use of virtual fixtures. This is done using the standard RD&T module to first create a positioning system for the part. This positioning system should be using points based on 3D PMI data which specifies how the part is fixed in an assembly.

To be able to complete the first step of creating a positioning system for the part, the following data is necessary:

- CAD data of part (**jt-file**)
- 3D PMI data

a) Import jt-file

The first step involves clicking on **New** to get a entirely new project. Then the jt-file of the part needs to be imported in the RD&T software. This involves clicking on **Handle Parts** which will open up a window of all defined parts in the system (see Figure 4.12).

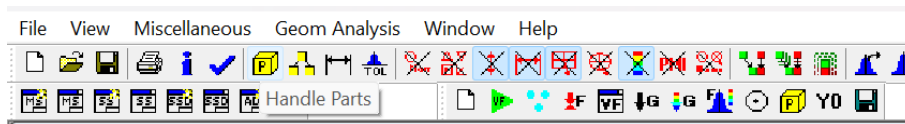
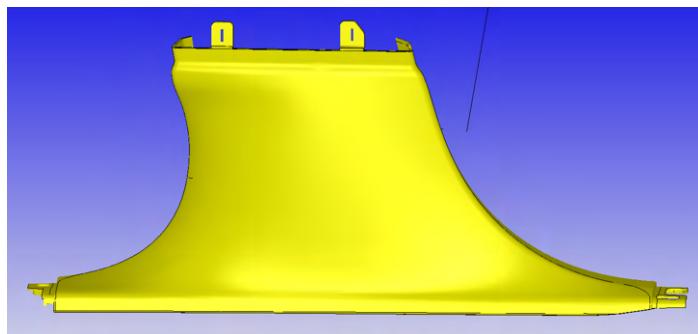
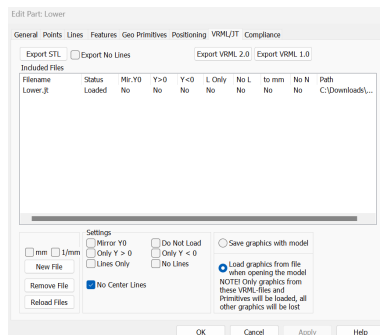


Figure 4.12: The Figure shows the standard RD&T interface and the **Handle Parts** button.

The user must then click on **New** to create a new part in the system. A new window opens up that allow the user to change preferences of the part according to needs. In the **VRML/JT** window, the jt-file of the part can be imported by clicking on **New File** (see Figure 4.13a). The user can then click on **Fit** in the right side of the interface to see the imported part. If the part is not shown, it might be necessary to click on **Miscellaneous** and **Reload VRML Files**. A window then pops up and if the user clicks **Load All**, the jt-file is reloaded to the software which should allow the user to see its geometry. The jt-file has been downloaded from Polestar's Active Workspace portal. In this demonstration, the part "B-Pillar Lower LH" is used. Figure 4.13b shows how the jt-file looks once it has been succesfully loaded into the software.



(a) VRML/JT window.

(b) The part in the model view.

Figure 4.13: Importing part Lower and seeing it in the model view

b) Create points from 3D PMI data

The second step involves creating points of specific x-, y-, and z-coordinates on the part, which will be used to create the positioning system. This is done by clicking on **Handle Parts** again. The part in the list can then be opened up to see the part preference interface. Then enter the window **Points** (see Figure 4.14).

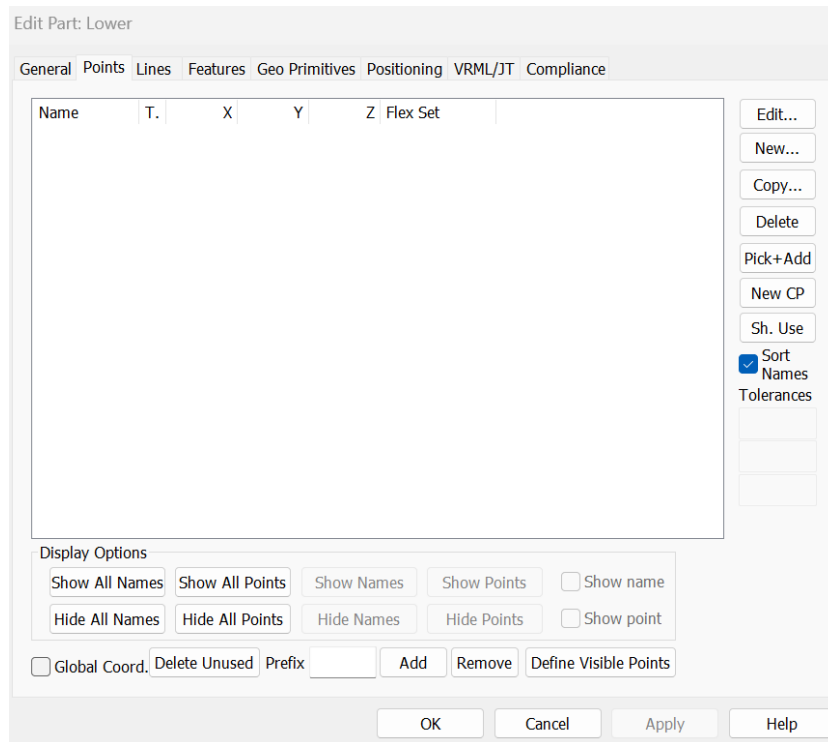
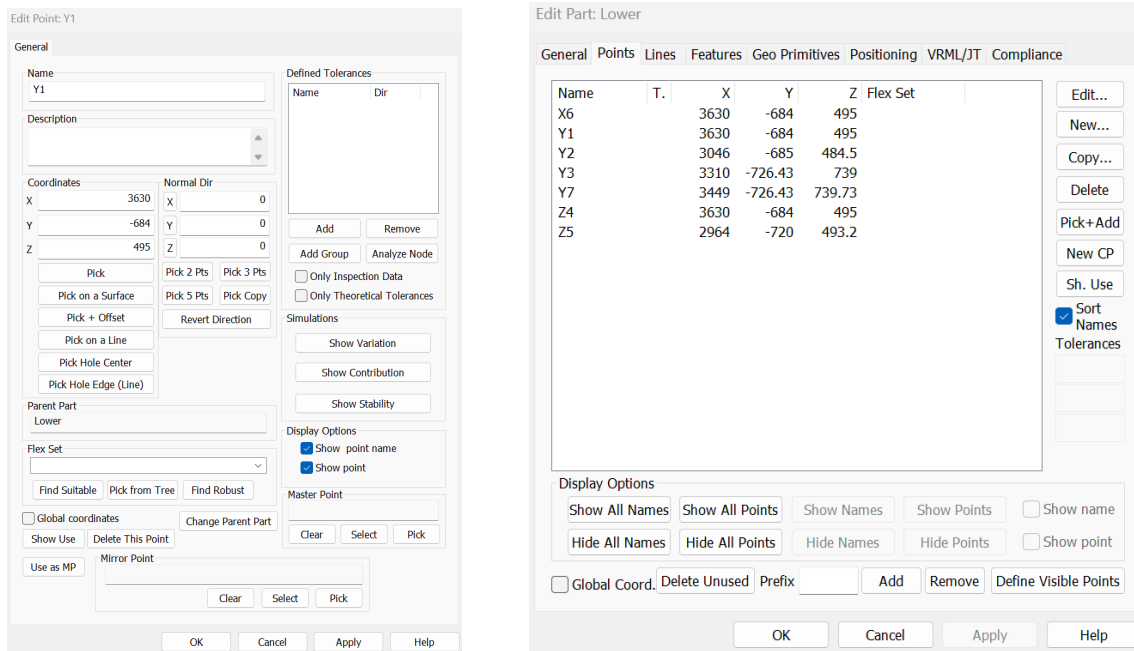


Figure 4.14: The points window where points can be created and placed on a part.

In this window, new points can be created by clicking on **New**. The point can then be specified, either by clicking on a specific surface, line, etc. on the model, or by entering specific coordinates. The first step is to create all the points that exist in the 3D PMI data for the part. These points are either of type X, Y, or Z, and they describe in which direction the part is locked. For example, for point Y1, Figure 4.15a shows its coordinates. This is done for all points that lock the part in place from the 3D PMI data. A list of all these points for the part B-Pillar Lower LH can be seen in Figure 4.15b. As can be seen, there are seven points which were brought from the 3D PMI data. Four points that lock the part in the Y-direction, two that lock in the Z-direction, and one that lock in the X-direction. This means that the part is over constrained, but it is also a non-rigid part in a complex assembly.

4. Result



(a) Coordinates of point Y1.

(b) All newly created points for the part.

Figure 4.15: The procedure of creating points from 3D PMI data that later can be used in the positioning of the part.

c) Create positioning system

Once all points have been created, a positioning system can be implemented. The first step involves going to **Handle Parts**, click on the part in the list, and go to the **Positioning** window (see Figure 4.16). Here the user can decide which kind of positioning system that should be implemented. As a preparation for the scanning process later on, a positioning system of 6 directions should be implemented. Therefore click on **6 Directions**.

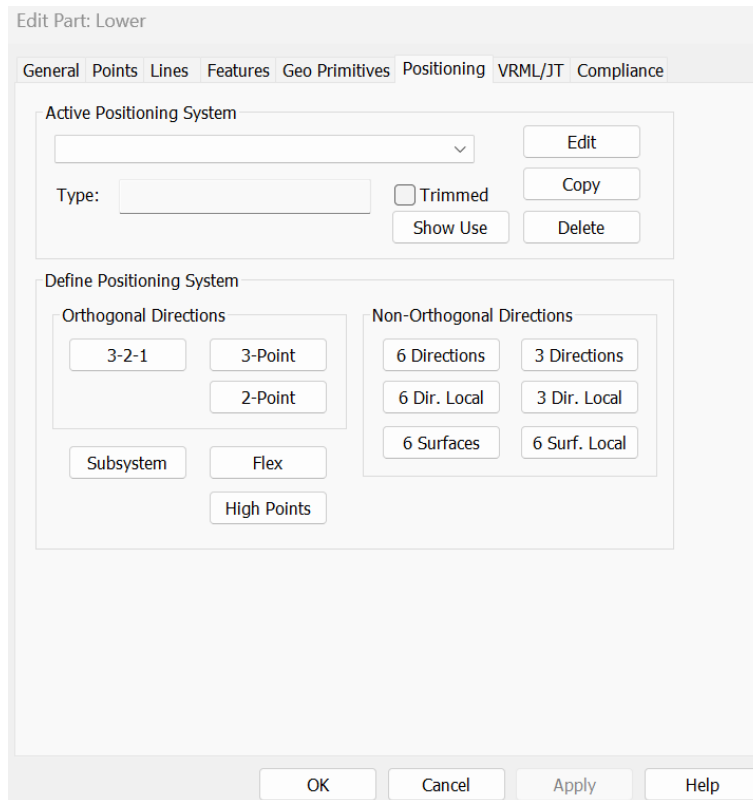


Figure 4.16: The available types of positioning systems to implement. In this step a 6 direction positioning is implemented.

A window pops up which allows the user to specify which points that should be used in the positioning system (see Figure 4.17). As can be seen, there are three points for A (A1-A3), two points for B (B1-B2), as well as one point for C (C1) (See under Local). Together these points can lock a part in all nine degrees of freedom. In this case, the points for A represent the points for Y, B for Z, and C for X (see the previously created points in Figure 4.15b).

4. Result

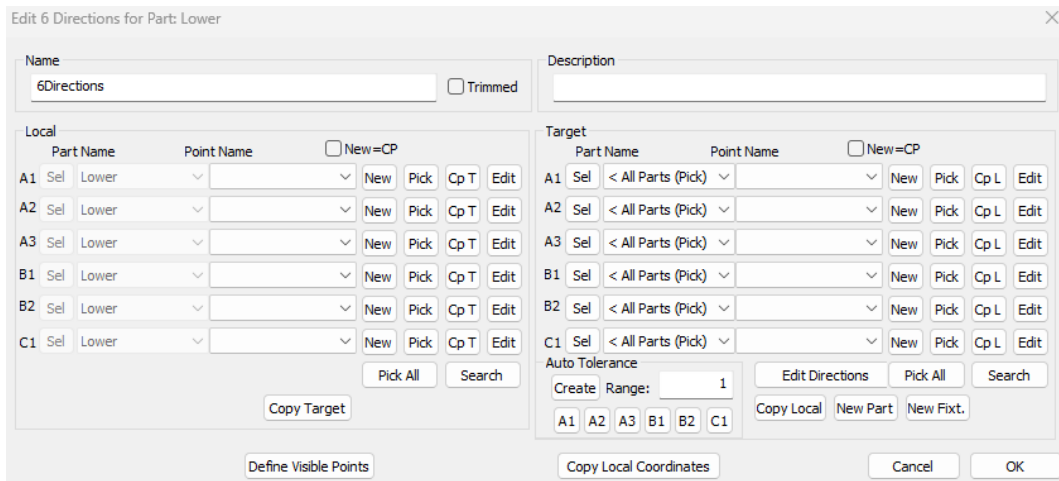


Figure 4.17: Overview of a 6 direction positioning system, with a list of points A, B, and C that will be used to lock the part.

The next step is to select the points that will be used in the positioning system. By clicking on the **Point Name** button for each point, the corresponding point can be chosen in the list. This is done for every point. This procedure can be seen in Figure 4.18.

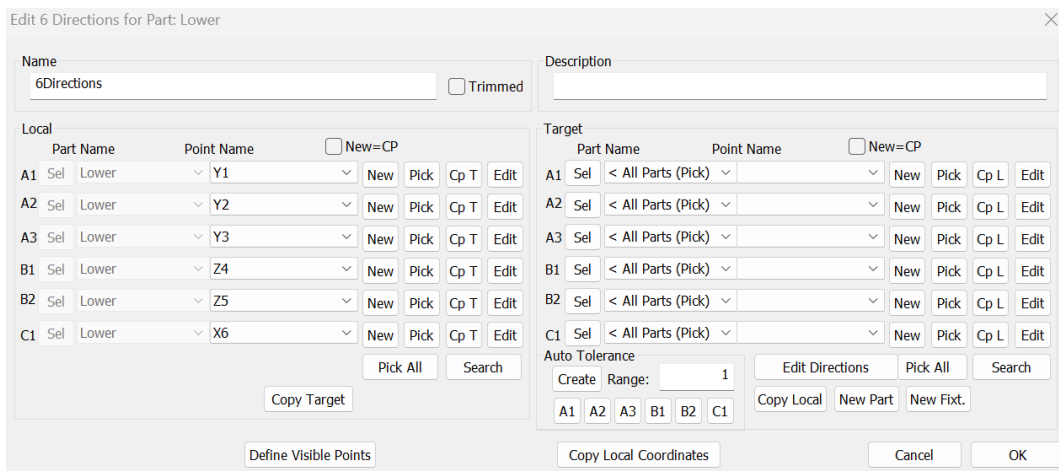


Figure 4.18: All points when they have been selected in the lists.

Once all the local points have been created, the next step is to match their target location. As there is no other part imported at the moment that the part should be assembled to, a fixture needs to be imported. This is done by clicking on **New Fixt.** and then **Copy Local**. The target points are now automatically chosen. See Figure 4.19.

4. Result

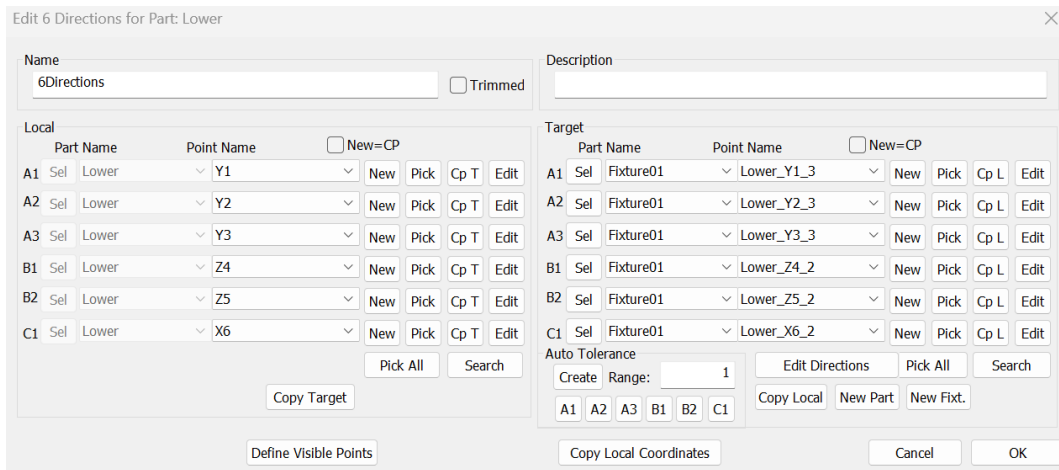


Figure 4.19: The complete positioning system.

The next step is to edit the directions of the positioning system. This is done to make sure that the model locks the part in all degrees of freedom. Therefore click on **Edit Directions**. A new window opens up that allow the user to choose the correct direction for each point in the system (see Figure 4.20). As mentioned before, A1-A3 lock in the Y-direction, B4-B5 in the Z-direction, and C6 in the X-direction.

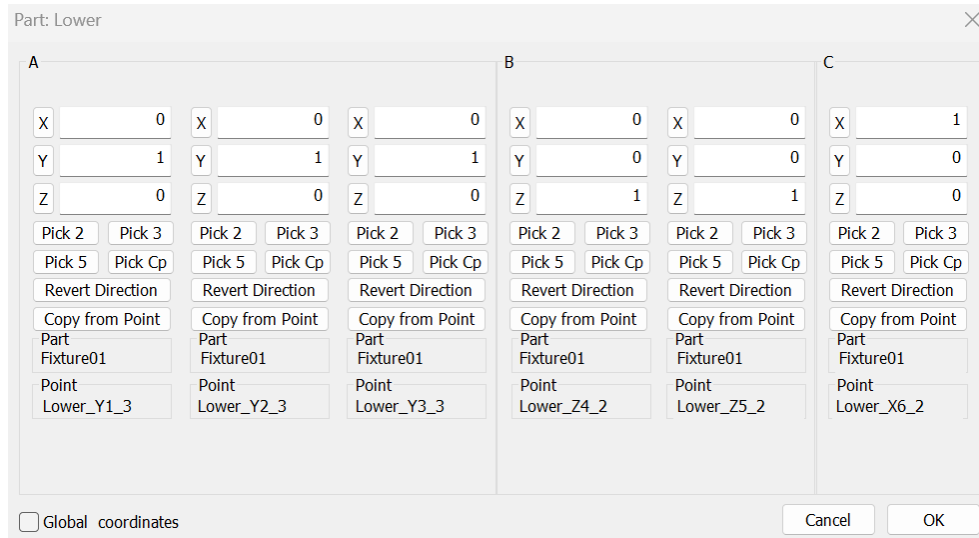


Figure 4.20: The window for editing the direction of each point.

The remaining part before moving on to the next module is to save the file as an RD&T file with a suitable name. This part will be used in the virtual fixture module described in the next section, to optimize the location of the spheres in order to scan the part in the most efficient way. The output of this step will be:

- A file saved in RD&T that contains the part and positioning system (**rdt-file**)

4.3.2.3 Step 2: Virtual Fixture - Optimize virtual fixture sphere location using the Scan Planning toolbar

Once a positioning system is determined for each part, the next step is to work with planning for the virtual fixture process in RD&T. To be able to complete this step, the following data is necessary:

- The file from previous step that contains the part and positioning system (**rdt-file**)
- A midsurface mesh of the nominal part CAD (**either a fem-, inp-, dat-, bdf-, nas-, blk-, ecd-, or k-file**)

a) Import mesh and rdt-file containing the part and positioning system from previous step

The work involves the Scan Planning toolbar. The first step is therefore reached by first going to **View**, then making sure that the **Plan Scanning Toolbar** is marked. This will insert the tool bar that can be seen in Figure 4.21.



Figure 4.21: The Plan Scanning toolbar.

The first step is to start a new project by clicking on **New** in the virtual fixture toolbar. Save this project as a new file to let the software find the correct pathway. Then click on the green VF symbol **Create Model**. This will open up a window that asks the user which file that should be imported. The first file is a mesh of the part that will be used during calculations. This mesh has been prepared beforehand as it is currently not possible to do meshes in RD&T. The mesh is a mid-surface mesh of size 2mm. See Figure 4.22 to see how the mesh of part B-pillar Lower LH looks in the software close to the surface.

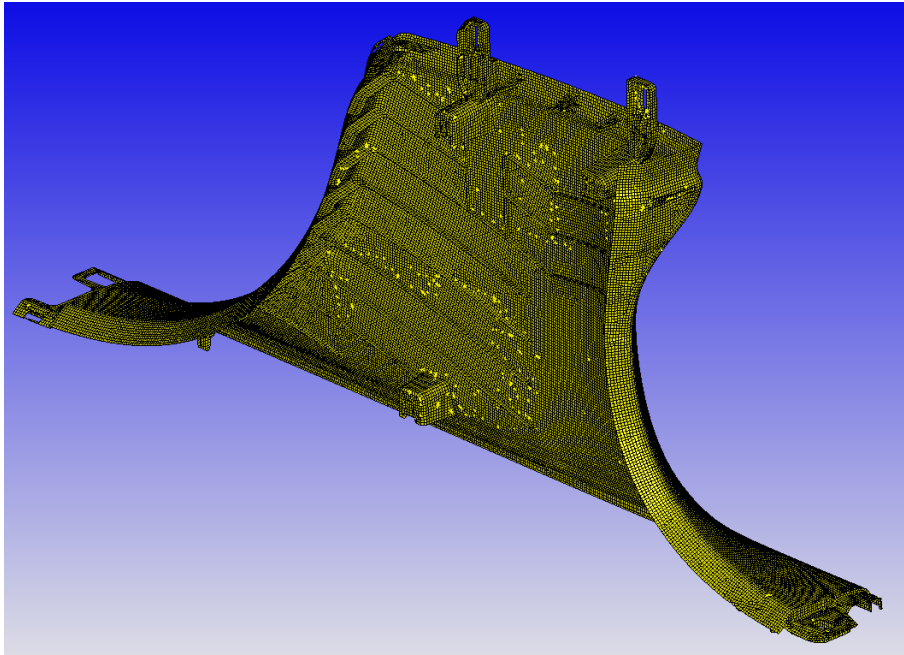


Figure 4.22: A close-up of how the mesh looks once implemented in RD&T.

Once the correct file mesh has been selected, a new window will immediately open, telling the user to select another file to import. This is the rdt-file which contains the positioning system explained in the previous subchapter. These two files are necessary for the scan planning tools to work.

b) Set the locations and directions of the spheres and modify the plane direction

Once the two files have been imported correctly, another window called **Sphere Alignment** comes up. This window allows the user to place the locations of three spheres by manually clicking on specific nodes in the mesh. It also allows the user to place the direction of the gravity plane. There are some important notes when placing the spheres. They should preferably be located on flat surfaces perpendicular to the direction of the gravity, so the spheres have a stable grip on the part during the scanning process. Any kind of movement, tilting, or gliding of the part may disrupt the scanning results. They should also be spread out so they cover up most of the part surface in order for the part to remain stable during the scanning process. It is also problematic if the spheres are placed too close to the edges of the part, as it can be difficult to match the scan data and nominal mesh in later stages due to the software being unable to find the spheres. The plane direction should go upwards from the scan surface. See Figure 4.23 for how the sphere alignment looks in RD&T.

4. Result

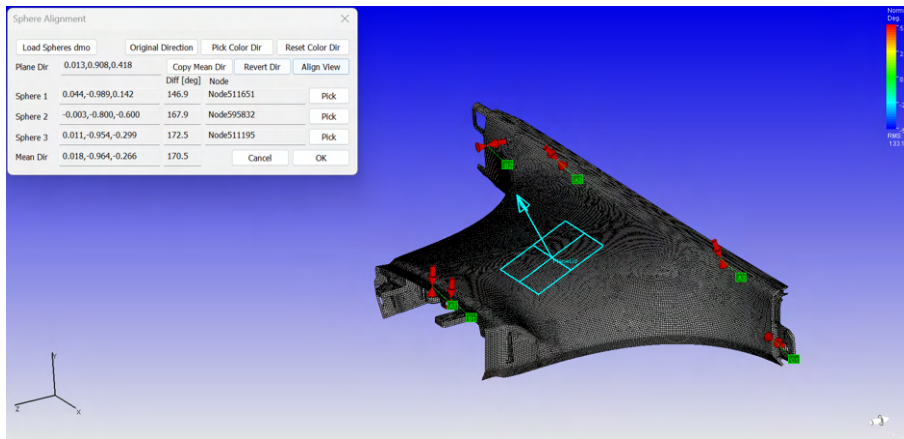


Figure 4.23: The sphere alignment window, telling in which node the sphere is currently placed.

Once the plane direction and sphere placement have been set and the user presses **OK**, another window pops up. This window allow the user to modify the newly created positioning system containing the three spheres, as well as three other points. The important thing here is to change the direction of the spheres and make sure they are located on the correct side of the part. As the top side will be scanned they should be placed on the other side. Therefore their direction is changed to the positive y-direction. The other three points B1, B2, and C1 do usually not have to be modified but are elected automatically by RD&T (see Figure 4.24).

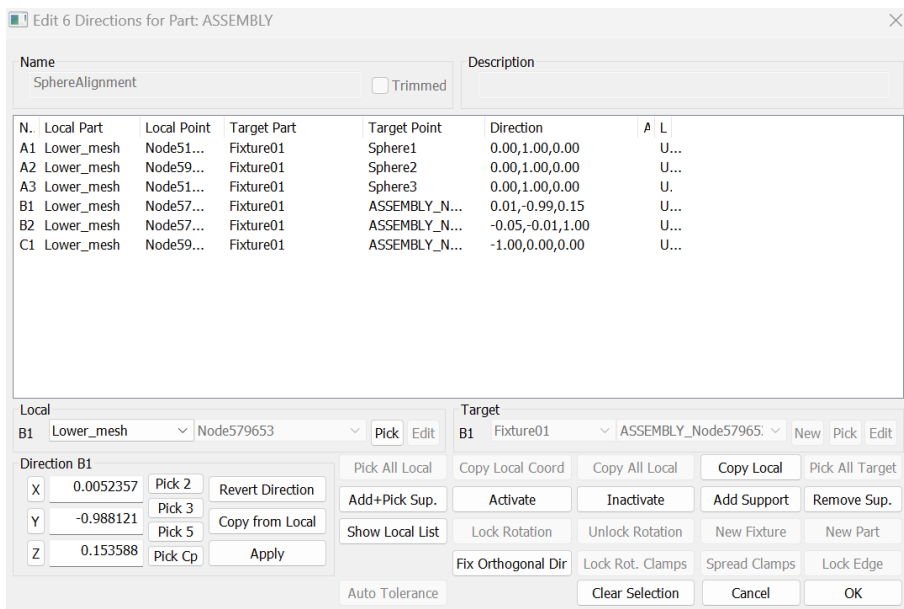


Figure 4.24: The newly created positioning system containing the spheres.

Once the user presses **OK** a new layout toolbar and layout window is presented that will be an instruction for how to build the fixtures containing the spheres for the scanning process. One can notice that the spheres now have the correct position

below the part. However, before printing this layout some other things will be performed first. Therefore click on **Quit** on the layout toolbar. This layout does not need to be saved yet.

c) Change the direction of gravity (if needed) and perform analyses to see if sphere alignment setup is optimal

In the VF toolbar there are various tools that can be used to analyze if the current sphere alignment setup is optimal. First, one can notice in the bottom right corner an arrow that visualizes the direction of the gravity. This direction is currently pointing in the x-direction which is incorrect based on how the spheres are placed and the geometry of the part. Therefore click on **Gravity Direction in Measurement Fixture**. In the new window the direction of the gravity can be chosen. For this model, the gravity should have direction $Y=-1$. See Figure 4.25 for the results after the direction of the gravity has been changed. It now points downwards which is correct based on how the part will be placed on the spheres.

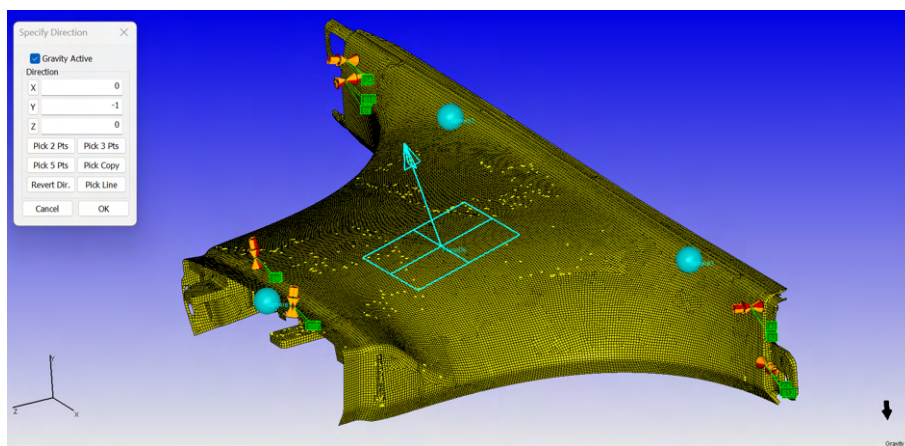


Figure 4.25: The window allowing for the direction of the gravity to be altered.

Once this is done press OK. The user can now do different analyzes, such as gravity analysis and fixture sensitivity analysis. These tools are used to analyze if the current sphere alignment setup is preferable or if it need to be altered. For example, when clicking on **Calculate Gravity in Measurement Fixture** in the scan planning toolbar, the software will do some calculations and give a result of how the part will be deformed by gravity when being placed on the spheres. As can be seen from Figure 4.26, most areas are green showing that there is no affect of gravity. However one area is red which shows that the gravity is affecting the part. This may be because of the special geometry of the part, and that the spheres are located quite far away from each other. However as they need to be placed on flat surfaces it may be difficult to find the optimal spot.

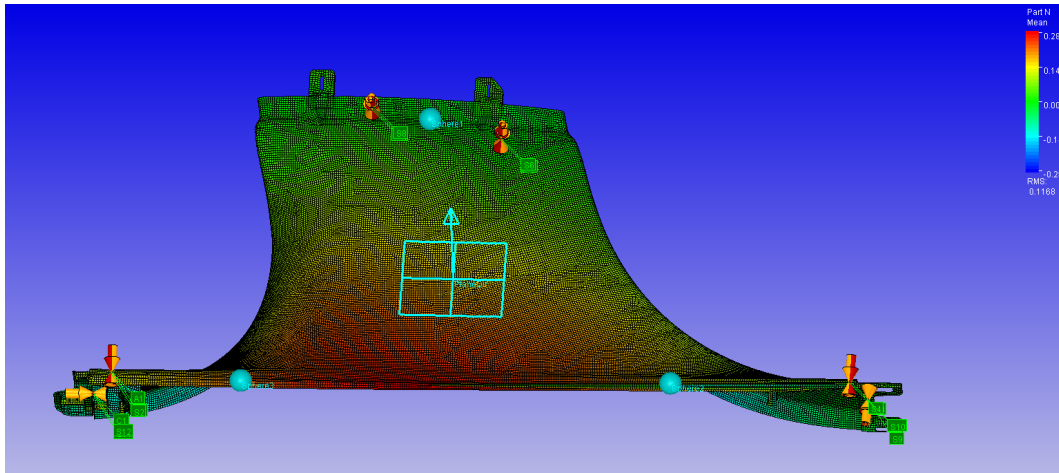


Figure 4.26: The model after using the gravity analysis tool. The colored areas visualize whether the areas are affected by gravity or not.

The user can also do a fixture sensitivity analysis by clicking on **Check Fixture Sensitivity**. The part material properties can also be specified by clicking on **Edit Part Material**. As one can notice, there are currently two material types - aluminium and steel, as the new virtual fixture module is optimized for being used in sheet metal cases. However as only plastic parts were used in this case study it was impossible to get the correct elastic modulus at this stage. Therefore nothing was changed in this window.

d) Collect the sphere alignment layout for the scanning procedure

Once all of the previous steps are done, it is time to get the sphere alignment layout and use this for building the physical sphere fixtures. Therefore save the model and then click on **Sphere Alignment**, click on **OK** two times to pass through the windows as these options have already been optimized. The layout will pop up and this is the guide for building the sphere fixtures. Either print this document as a PDF or use the layout directly on the computer when building the spheres. See Figure 4.27 for the layout.

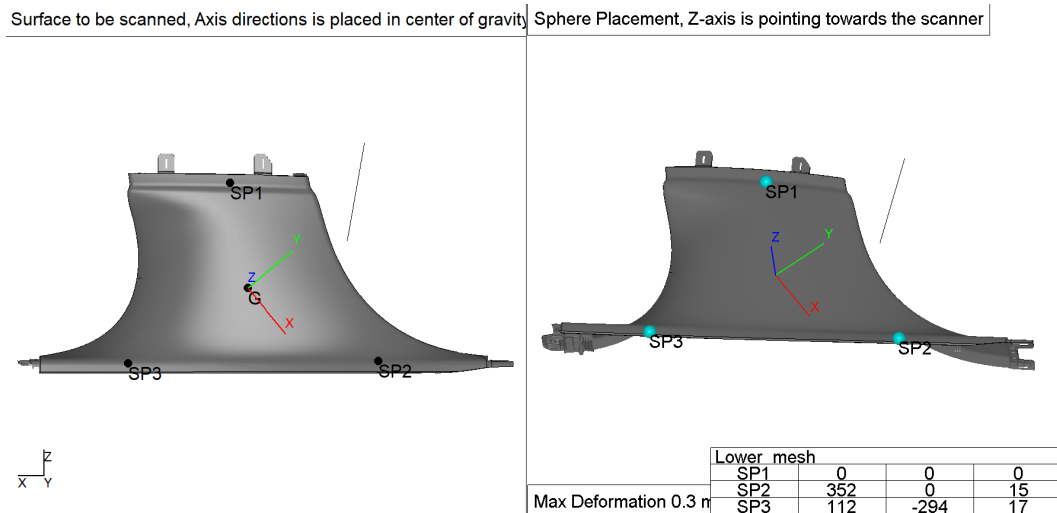


Figure 4.27: The sphere alignment layout.

The resulting files from this step that are of importance are the following:

- The RD&T file just created containing the part, mesh, and sphere alignment setup after VF processing which will be used to match the scan data later (**rdt-file**)
- An sphere alignment layout either printed or saved on the computer

The steps following the previous procedure involves the actual scanning process using Polyworks. It is not until the scan has been performed and the necessary files are obtained that RD&T is used again. Therefore the scanning & Polyworks procedure is explained in Appendix E.

4.3.2.4 Step 3: Black Box - Import scan data

Once the scanning procedure is completed and all necessary files are obtained from the Polyworks software (which is explained in Appendix E), the next step is to import the scan data to RD&T. To be able to achieve this, the following files are necessary:

- The RD&T file from the previous step which contains the part, mesh, and sphere alignment setup after VF processing (**rdt-file**)
- Surface scan data as an STL file which must be named NotAligned.stl. It contains the polygonal model of the scanned surface (**stl-file**)
- Boundary scan data as an txt file which must be named Boundary.txt. It contains a point cloud of all the boundary points (**txt-file**)
- All features as an DMO file which must be named Features.dmo. It contains all features with their nominal position and size and deviation based on the scanning. These features also include the spheres and gravity plane (**dmo-file**)
- A midsurface mesh of the nominal part CAD (**either a fem-, inp-, dat-, bdf-, nas-, blk-, ecd-, or k-file**)
- Part CAD (**jt-file**)

It is important that all of these files are located in the same folder on the computer for the next steps to work. It is also important that they files have the exact names as mentioned before. Likewise, the features such as the surface points, spheres, and gravity plane need to have correct names according to what was explained in Appendix E. Otherwise RD&T will not be able to track the correct files.

a) Open up the rdt-file from step 2 and obtain the exact positions of the spheres from the scan data

Once the file containing the sphere alignment from step 2 has been opened up in RD&T, the first thing is to get the exact positions of the spheres in the sphere alignment by loading the dmo-file containing the features. This can be done by clicking on the **Sphere Alignment** icon containing three spheres in the Scan Planning toolbar, then clicking on **Load Spheres dmo** (see Figure 4.28). The user can then select the file named Features.dmo, and the location of the spheres from the scan will be loaded into the software. Press OK to save the settings.

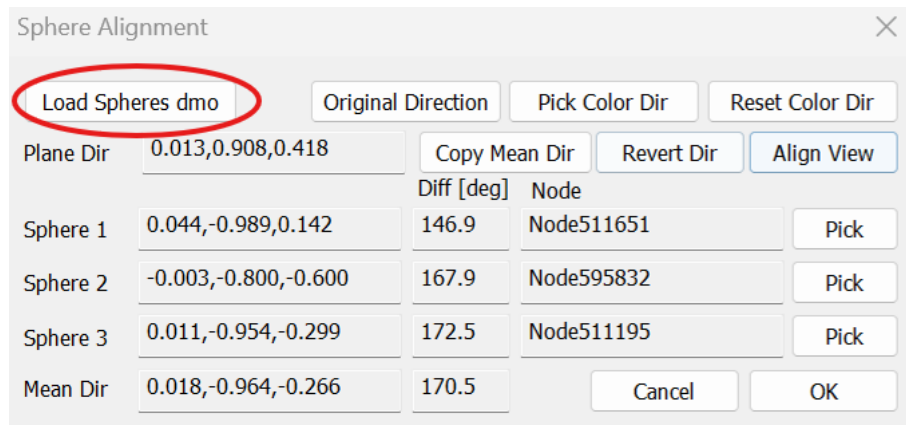


Figure 4.28: The tool for loading the exact locations of the spheres in the sphere alignment window.

b) Run the Black Box

The next step is to import the scan data to the model. First, one need to make sure the Black Box VF toolbar is shown in the interface. This is done by clicking on **Miscellaneous**, then clicking on **Black Box VF Toolbar** and making sure it has a check mark on it. Figure 4.29 shows the Black Box VF toolbar.



Figure 4.29: The Black Box VF toolbar.

The next step is to click on the green BB symbol in the toolbar named **Run Black Box**. Once the user presses this button, a window pops up which allows the user

to change input data for the coming simulations. Here the percentage of clamped nodes can be altered to 5 (see Figure 4.30a). Also make sure that the **Boundary Morphing** option is marked. After the user presses OK, another window comes up. Here the user should make sure that the options for **Create Boundary Part** and **Boundary Measures** are clicked (see Figure 4.30b).

The screenshot shows a dialog box titled "Enter Input" with a close button (X) in the top right corner. It contains several input fields and checkboxes:

- Percentage of clamped Nodes: 5
- Initial No Hit Angle: 30
- No Hit Angle: 5
- Final No Hit Angle: 30
- Needle Length: 10
- Max NURBS Size (0=All): 10000
- KD Tree
- Boundary Morphing
- Clamp Boundary

At the bottom right, there are "Cancel" and "OK" buttons.

(a) Specifications regarding the BB calculation. The percentage of clamped nodes was changed to 5 and the boundary morphing option was selected.

The screenshot shows a dialog box titled "Enter Input" with a close button (X) in the top right corner. It contains several input fields and checkboxes:

- Search Distance: 3
- Number of Points: 10
- Create Boundary Part
- Boundary Measures

At the bottom right, there are "Cancel" and "OK" buttons.

(b) Specifications regarding the BB calculation. The options for creating a boundary part and boundary measures should be selected.

Figure 4.30: Settings for the BB calculations.

Once these alterations have been made and the user presses OK, the software will proceed with importing the scan data. If everything proceeds correctly, some windows will pop up close to the features imported from PolyWorks, which will show the deformation of the scan data from the nominal mesh in these points. Figure 4.31 shows how the model looks once the Black Box calculations have been completed and the scan data has been imported correctly to the software. The points show that there is some variation in the scan data from the nominal mesh. The points which show the variation are the surface points extracted from the features file that was imported from PolyWorks. These points were also created and used in the initial positioning system in order for RD&T to correctly match these points with the surface points from PolyWorks.

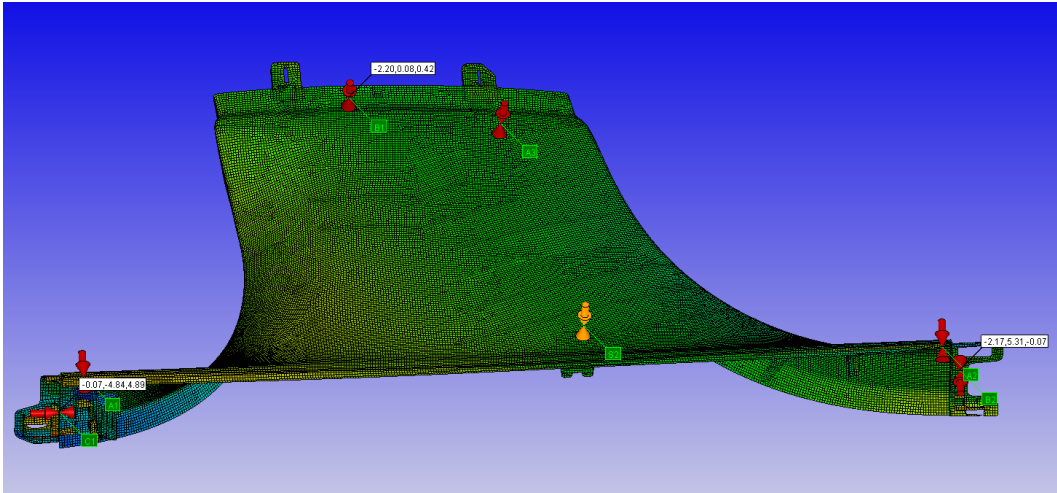


Figure 4.31: The model after the scan data has been imported. The text windows show that there is some variation in the scan data from nominal values.

If all calculations are successful, a new text file should have been created in the file folder, which is explain in the next step. Therefore save the model and close it.

b) Track the newly created file in the folder containing the deformed mesh

Once the BB calculations have been made, one can notice that new files have appeared in the file folder containing the rdt-file. See Figure 4.32 for how these files look in the folder.










 Lower_mesh_VF	2025-04-22 15:20	DirectModel Docume...	9 147 KB
 Lower_mesh_clamped_poly	2025-04-22 15:20	Text Document	6 814 KB
 Lower_mesh_free_BF	2025-04-22 15:20	DirectModel Docume...	9 148 KB
 Lower_mesh_free_poly_BF	2025-04-22 15:20	Text Document	6 814 KB
 Lower_mesh_fixture_gravity	2025-04-22 15:19	Text Document	6 814 KB
 Lower_mesh_free_poly	2025-04-22 15:19	Text Document	6 814 KB
 Lower_mesh_g_effect	2025-04-22 15:19	Text Document	6 814 KB
 Lower_mesh_poly	2025-04-22 15:18	Text Document	6 814 KB
 LogFile	2025-04-22 15:20	Text Document	3 KB

Figure 4.32: The files created in the file folder once the BB calculations are completed in RD&T.

Each file contains various information that may be of use for further analysis. Below is a short explanation of each file, where X represents the name of the original mesh file:

- X_clamped_poly.txt = the part in the fixture (is shown in the model interface after the BB calculations).

- X_fixture_gravity.txt = the effect of gravity on the part in the fixture (shown after the BB calculations, can also be visualized in the VF modeling stage).
- X_free_poly.txt = the result of "fem_poly" - "fem_g_effect".
- X_free_poly_BF.txt = what is shown in the VF BB as "free" (most likely a best fit of "free_poly" above).
- X_g_effect.txt = the effect of gravity on the three fixtures.
- X_fem_poly.txt = shape plus gravity of the three spheres.

The file that is of importance for further analysis in this case is X_free_poly_BF.txt. Therefore the output of this step is the following:

- A text file containing the deformation of the scan data in each mesh node compared to the nominal mesh, thus showing the geometric variation in each node. This file is named X_free_poly_BF.txt and is created automatically after previous BB calculation in the same folder as the previous RD&T model.

4.3.2.5 Step 4: Virtual Assembly - Using the scan data to analyze part variation

Once the text file containing the deformation in each mesh node is obtained from the previous step, the next objective is to use this data to verify the geometry of the part. This will be achieved by first creating a new model, then importing the nominal mesh of the part that needs to be analyzed, then applying the scan data to the mesh by importing the text file which automatically will create tolerances in each mesh node, where the number describes the geometric variation in millimeter in that node. After this, the nominal meshes of parts that the part to be analyzed is assembled to with clips or screws also need to be imported. The compliance tool can then be used to search for contact points between the scanned part and surrounding nominal meshes, which is similar to the current physical nominal buck process. As two parts - Lower and Intermediate, have been scanned and analyzed during the case study, both of them will be imported in the same model. However it is the choice of the user of this method if it is of interest to study one or several parts at a time. The following files and data are necessary for this step:

- A midsurface mesh of the nominal CAD of both the part that is to be analyzed as well as all surrounding parts the part is assembled to (**either a fem-, inp-, dat-, bdf-, nas-, blk-, ecd-, or k-file**)
- 3D PMI data
- The text file in the previous step with name X_free_poly_BF.txt

a) Create a new RD&T model and import nominal mesh of parts and scan data to create tolerances

The first step involves creating a new RD&T model and then importing a new part. However no jt-file is needed at this stage, only the nominal mesh. In this case, part Lower is described, so a midsurface mesh of part Lower is imported. A mesh can be imported by going to **Handle Parts**, then **New**, then the **Compliance** window

4. Result

(see Figure 4.33 for how the compliance window looks).

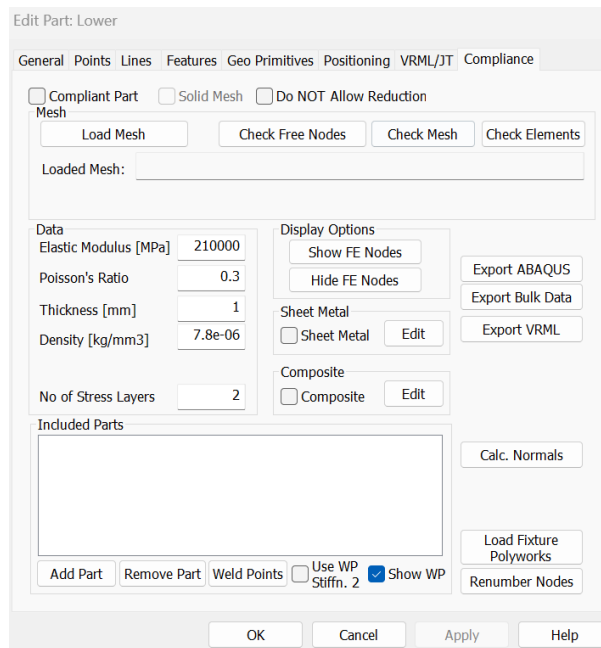


Figure 4.33: The compliance window where a mesh can be imported.

A mesh can then be loaded by simply clicking on **Load Mesh**. The user can then choose from the initial options (inp-, dat-, bdf-, nas-, blk-, ecd-, or k-file), however, the user can also click to search for all files which also allow to import a fem-file for example (as is done in this case). Once the file has been selected and chosen, one can notice that material properties can be altered to the user's desire. In this case, the plastic part Lower has an elastic modulus of 2350MPa and a thickness of 2.5 millimeter. Poisson's ratio and density are not altered as information about these were not found. Also make sure that the box **Compliant Part** is marked, which is necessary for non-rigid analysis. See Figure 4.34 for how the imported mesh looks in the model with the compliance window open.

4. Result

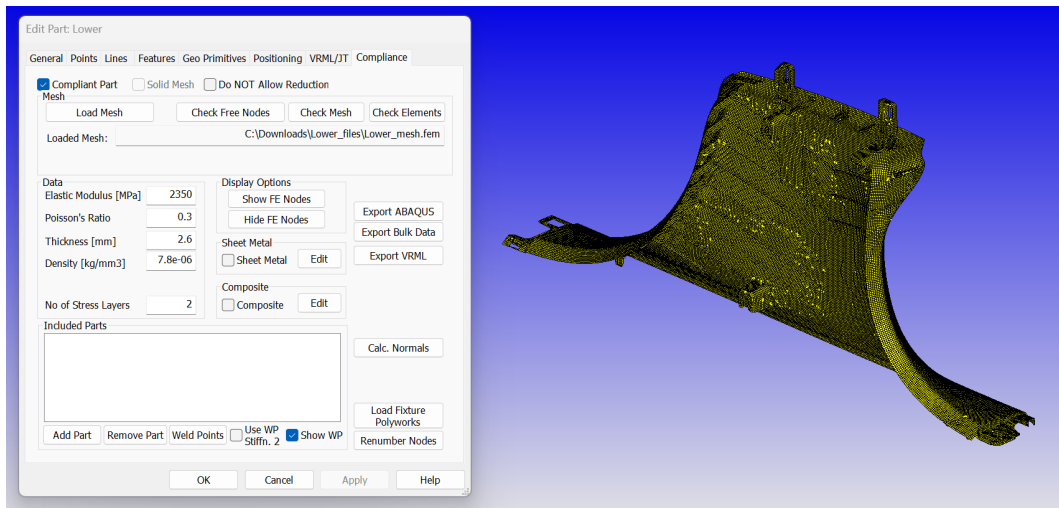


Figure 4.34: The compliance window and the model visualizing the mesh.

The next step is to import the text file containing the deformation. Once this text file is imported, tolerances will be created for that part, and each tolerance tells of the deformation from the nominal mesh node. For this a toolbar called Virtual Assembly Toolbar is used. Therefore, click on **View** in the top-left side, then make sure that **Virtual Assembly Toolbar** is marked (see Figure 4.35).

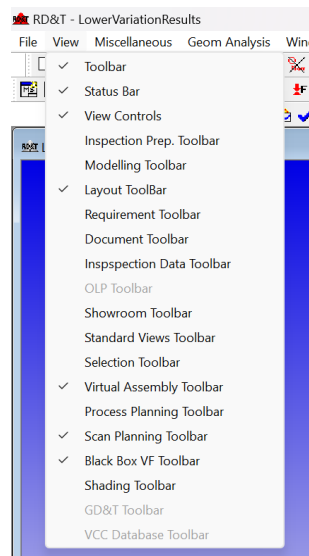


Figure 4.35: Marking the Virtual Assembly Toolbar.

Once Virtual Assembly Toolbar is shown in the window, the user can click on the button **Load Polyworks** to load the text file (see Figure 4.36).

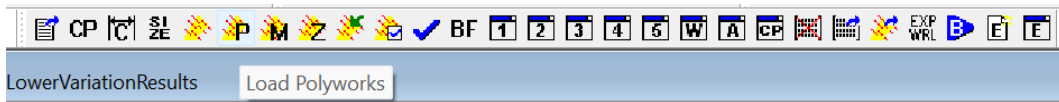
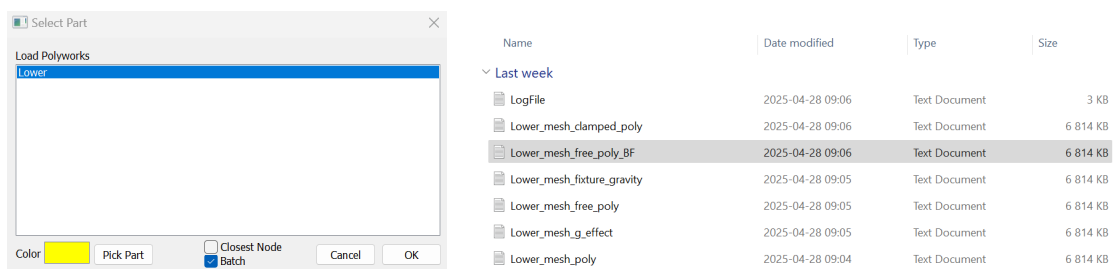


Figure 4.36: The tool for loading polyworks data.

A new window then pops up that allows the user to select the correct part. As scan data for Lower is to be implemented first, this one is selected (see Figure 4.37a). Once the part is selected, another window comes up to choose the correct text file. It is important that the text file is in the same folder as the RD&T model. See Figure 4.37b how the correct text file is named. Then press OK.



(a) Choose the part which has the scan data. (b) Lower_mesh_free_poly_BF contains the scan data.

Figure 4.37: Procedure of importing scan data for the part.

Now the scan data has been imported and tolerances have been created for the part. To assure that the data has been imported correctly, go to the **Handle Tolerances** button which is visualized by a blue variation diagram and TOL logo (see Figure 4.38).

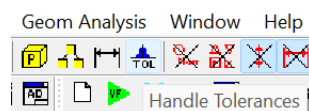
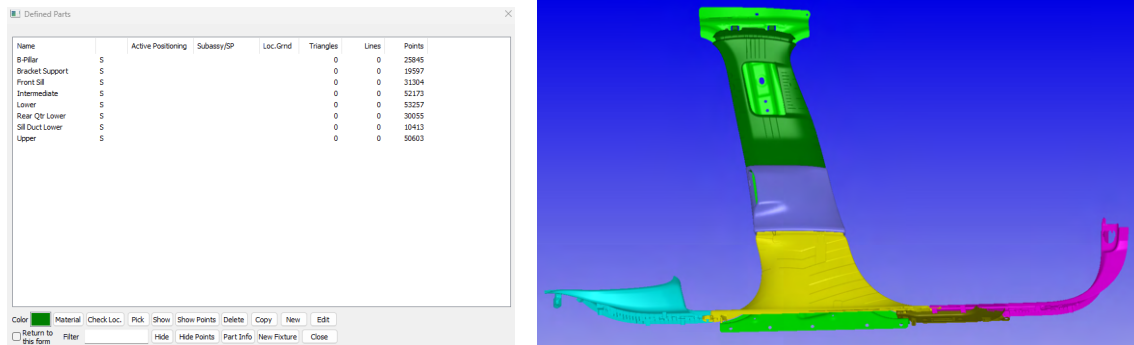


Figure 4.38: The button for handling all tolerances.

The window for all defined tolerances will now appear. At first sight, there are no tolerances visible. That is because the tolerances are created as local tolerances for the Lower part. Therefore one must make sure the option for **Show Local** is marked first. A list of all tolerances then appears. These tolerances show the variation in each mesh node as an offset, which is the deformation in the scan data from the nominal part in millimeter (see Figure 4.39).

(be aware that there are no lines showing the mesh nodes in this Figure, a visibility which can be changed according to preferences in the settings menu to the right). Parts Lower (yellow) and Intermediate (dark blue) are the ones that have been scanned, whose geometric variation is to be analyzed.



(a) Part names involved in the assembly. (b) The assembly in the model view.

Figure 4.40: The assembly of parts involved in the analysis to measure parts Lower and Intermediate.

c) Create a "Superpart" that contains all nominal parts and weld them together

The next step involves creating what is referred to as a superpart. The superpart consist of all parts that are not of interest during the variation analysis, hence the nominal parts that parts Lower and Intermediate are assembled to. The parts in the superpart are then welded together so they always remain rigid in relation to each other. This is an important step as in a physical nominal buck, the nominal parts are not meant to bend or move. The part that will have its variation analyzed is inserted in this nominal, rigid environment to see if it has the correct geometry.

To create a superpart, go to **Handle Parts** again, then **New**. Name this part **Superpart** for easy recognition. Then go to the **Compliance** window. In this window the user can see a window called **Included Parts**. Below this window the user can add parts to the assembly. Therefore click on **Add Part**. A window with the list of parts in the model then comes up, so each one of interest is picked. In this case all parts except for Lower and Intermediate should be included in the superpart (see Figure 4.41). Make sure that the **Compliant Part** box is marked.

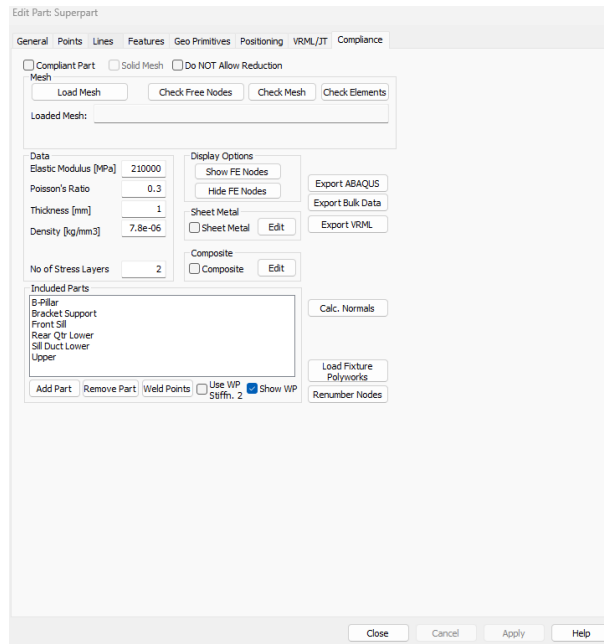
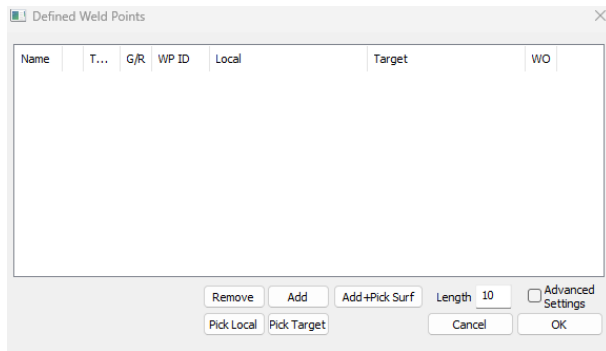


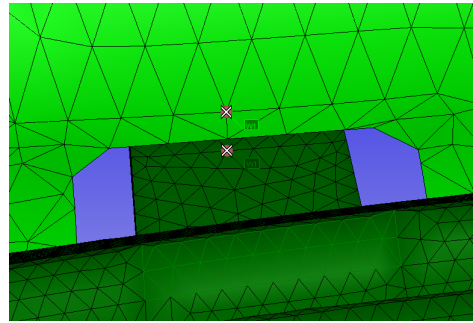
Figure 4.41: The included parts in the superpart.

The next step is to weld together these nominal parts so they represent the superpart. Therefore click on **Weld Points**. A new window then comes up which allows the user to define the weld points (see Figure 4.42a). The user can select local and target points for each weld point to weld together two parts. It is necessary that each local and target point is picked in a mesh node. One can also use the tool to add and pick a surface, which will automatically detect a target mesh node within a distance specified once a local point is picked. Once a weld point has been created, it will lock the part in that point in all directions. The goal is to lock all nominal parts together. For this demonstration, the automatic target detection will be used for demonstration. Therefore click on **Add+Pick Surf**. The user can then select a mesh node to create the local weld point (remember to turn on the black lines in the settings to see the mesh nodes). The software will then automatically detect a mesh node on a target part in the normal direction of that surface. If no node pair is found, the software will let the user know that the mesh node can not be selected. Figure 4.42b shows how the model looks once a weld point has been correctly created between parts B-Pillar and Upper. The user can then continue to create more weld points on other surfaces by left-clicking, or right-click which directs the user back to the list of defined weld points.

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(a) The tool for adding weld points.



(b) A correct implementation of a weld point, in this case between part Upper and the B-Pillar.

Figure 4.42: The process of creating weld points in the Superpart.

Continue to weld together all parts in the superpart. Be aware that nothing should be welded to the parts that have their scan data imported (Lower and Intermediate in this case). The exact spots of these weld points are not of great importance, the welds are only done to fasten these parts to each other. As each weld point also locks the parts in all directions, it is only necessary to do 1-2 weld points between every two parts. The importance is that the entire assembly is connected in the welding sequence. Therefore, one part does not need to be welded to all other parts in the assembly, just the one lying closest in space. If two parts have a big distance between each other, just alter the search distance and the software will be able to connect the node pairs. For this superpart, a total of 10 weld points were created (see Figure 4.43).

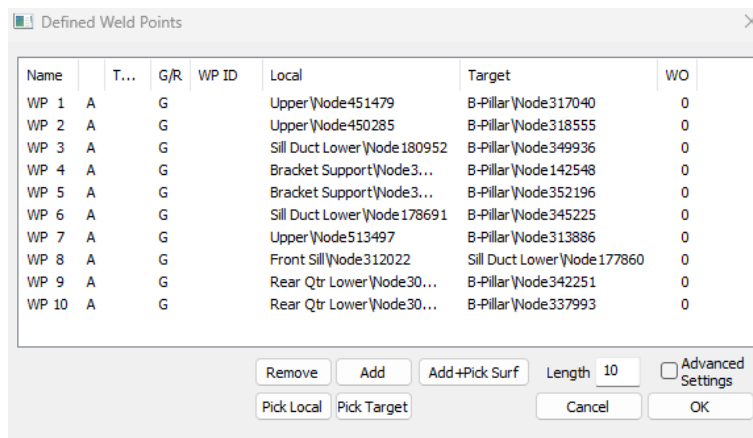


Figure 4.43: The list of all defined weld points to connect the superpart.

Once all weld points have been created, they can also be viewed in the model window (see Figure 4.44). Notice that none of the weld points are connected to parts Lower or Intermediate (the weld points W4 and W5 are welded between the B-Pillar and a bracket support placed inside Intermediate).

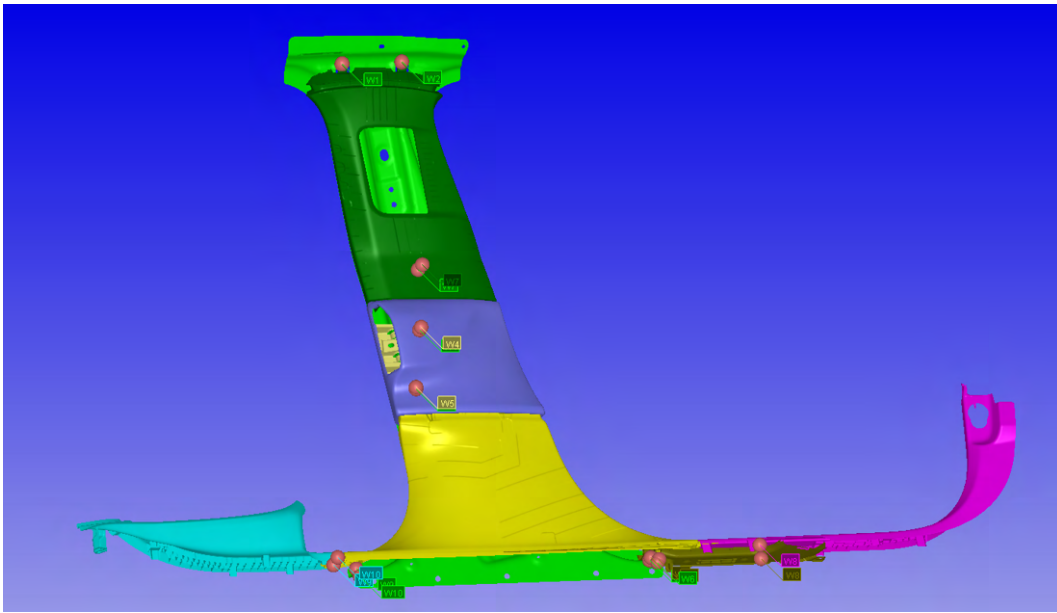


Figure 4.44: The newly added weld points can easily be recognized in the model window.

The superpart is now created and welded together. Realistically, the weld points would be placed on top of each other, however, this is not the case in RD&T. The parts will still have their original positions and orientations in space, just that they are connected forming an rigid assembly.

d) Create positioning systems for parts Lower, Intermediate, and Superpart

The next step involves creating positioning systems for each and one of the parts Lower, Intermediate, and Superpart. The Superpart has been welded together and the relation and fixation between the parts in the superpart is defined. However its fixation in space is not yet defined, just as the fixations in space for Lower and Intermediate are not yet defined, which is the next step.

It was mentioned at the start of this chapter that one necessary type of data for this step was 3D PMI data. This is needed for parts Lower and Intermediate in order to define their positioning systems. The process of creating reference points and positioning systems has been explained in earlier chapters. Therefore, start by defining the reference points for both Lower and Intermediate. For part Lower, the points in the list in Figure 4.45 were created.

4. Result

X6	3629.07	-684	494.219
Y1	3629.07	-684	494.219
Y2	3044.23	-685	484.731
Y3	3304.33	-725.423	741.387
Y7	3447.26	-725.405	745.68
Z4	3629.07	-684	494.219
Z5	2964.01	-724.15	495.712

Figure 4.45: The reference points for part Lower which is used to fixate the part in space.

Repeat the same process and create points from 3D PMI data for any other part in the assembly that will be analyzed (in this case part Intermediate). Once the points are created, implement a positioning system for each part. For both parts Lower and Intermediate, there are 7 reference points each which means that they are over constrained. The last reference point (Y7) can be used as a support point. To create a positioning system enter the part, then go to the **Positioning** tab and add a new **6 Directions** system. Then create the positioning based on earlier created points. However, one extremely important note is that each reference point in the positioning system needs to be picked from a mesh node. Therefore the previously created points from the 3D PMI data is only a guideline. The procedure is to pick each local point in the mesh node closest to the data point. For example, A1 represents Y1 and therefore the closest mesh node to Y1 should be picked. Make sure the points have the correct directions. For target part, a fixture can be added by clicking **Add Fixture**, and use this as target for all points. Realistically the target would be the other parts that Lower and Intermediate are assembled to, however this is not necessary in this step. The positioning system is only created to lock the parts in space. See Figure 4.46 the positioning system for Lower. Once done, press OK and repeat the same process for the other part (in this case Intermediate). The same fixture (Fixture01) can be used for both of these parts, it does not affect the model output.

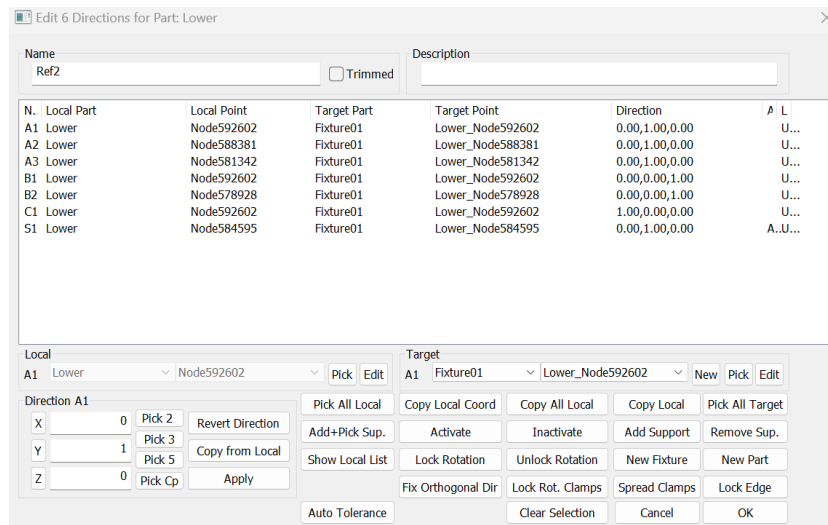


Figure 4.46: The positioning system for part Lower. It is important that each local point is picked in a mesh node, and that it fixates the part in the correct direction.

4. Result

A final positioning system also needs to be defined for the Superpart to lock it in space. As it is an assembly consisting of many different parts, it is not as straightforward regarding any 3D PMI data. Therefore it is the task of the worker to pick these points, but it should be logical in terms of how the points are meant to lock the parts regarding direction. A 6 directions positioning system should be created for the Superpart in the same manner as before. Three points were picked from the surface of the Superpart (one that lock in XYZ-direction, one in YZ-direction, one in X-direction), that were used for the initial A1-A3, B1-B2, C1 points. However, a large amount of support points were added for the Superpart. This was necessary, as one need to make sure that the Superpart is entirely rigid throughout its geometry during the simulation. Even though an elastic modulus of 210GPa was set earlier, this is an extra assurance that one can view the Superpart as rigid. A total of 33 support points were created for the Superpart in this case. Make sure that each one of the initial points as well as the support points lock the part in the correct directions in a logical manner. See Figure 4.47 for the finalized positioning system for the Superpart.

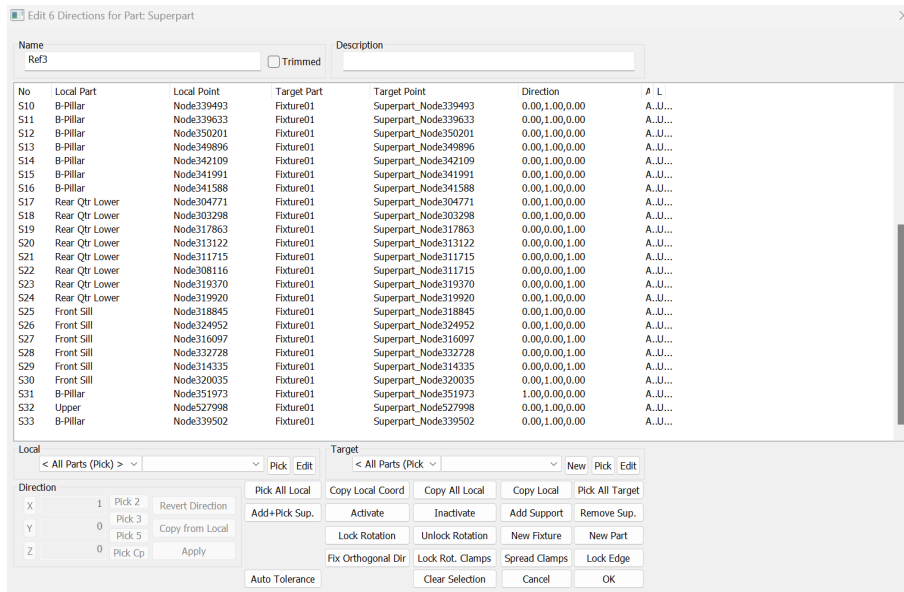


Figure 4.47: The positoning system for the superpart.

Once all positioning systems are created (for the parts to be analyzed as well as the Superpart), this can be seen in the model window (see Figure 4.48).

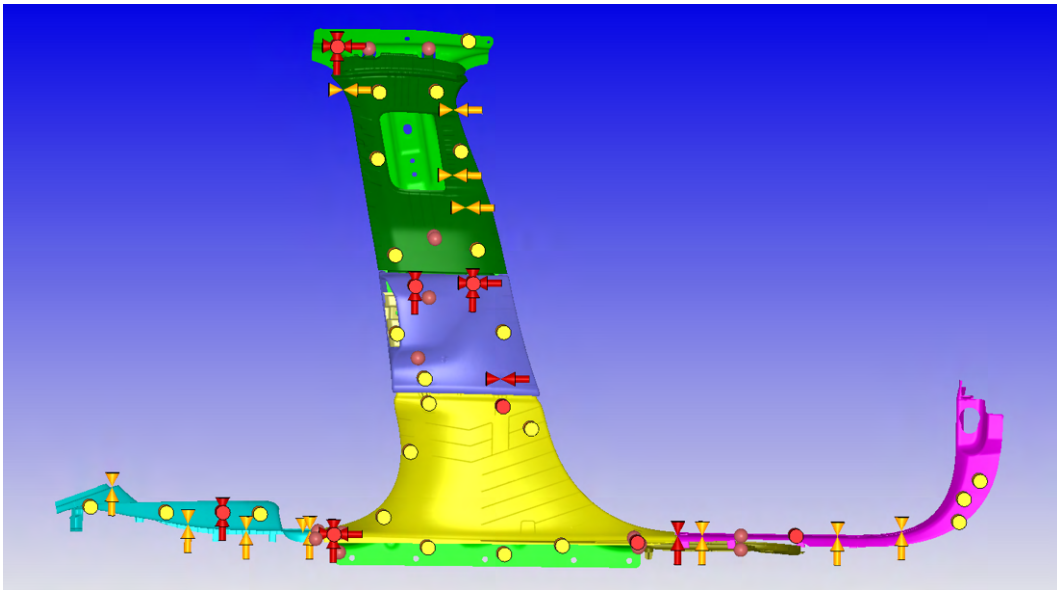


Figure 4.48: The complete assembly with all positioning systems implemented. Notice that there are a large amount of support points (yellow arrows) which are used in the positioning system of the Superpart to make it rigid.

e) Create an assembly, weld the scanned parts with the Superpart, and search for contact points

The next step is to weld together the scanned parts (Lower, Intermediate) and the Superpart as an assembly, which makes it possible to analyze contact points. This directly allows the user to see if the variation in the scan data (the tolerances for Lower and Intermediate) creates a contact.

An assembly first needs to be created. Therefore go to **Handle Subassemblies** where a new assembly can be created by clicking on **New**.

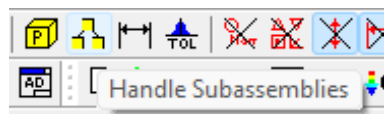


Figure 4.49: The button for handling subassemblies.

A window then comes up to change the assemblies according to preferences. The included parts in the system should be the Superpart, the parts that are to be analyzed (Lower, Intermediate), as well as the fixture that is used as target points in the positioning systems for each part (Fixture01). This part is included in the assembly, as a "local ground" needs to be selected. Use the tool **Local Ground** and select Fixture01. It is necessary to use this fixture as the local ground, because it is not possible to create weld points in a part that is a local ground. Therefore it would be problematic to use any of the other parts. See Figure 4.50.

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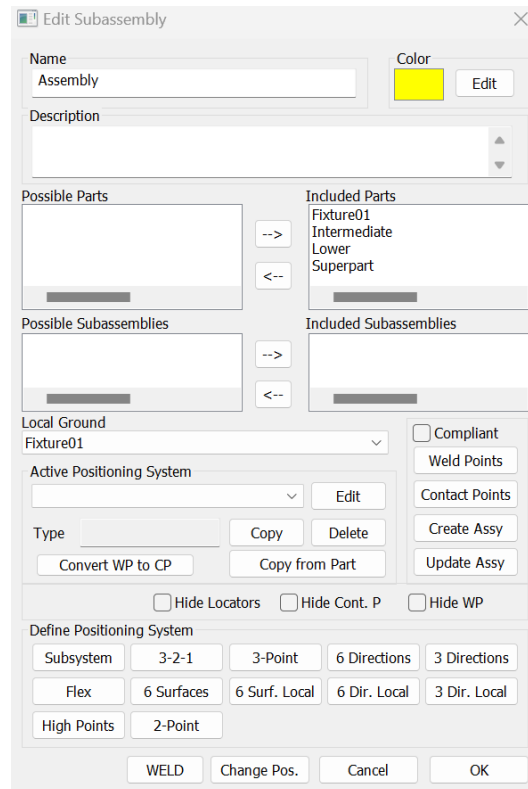


Figure 4.50: The window for editing the assembly. Both the Superpart and the parts that are to be analyzed should be included, as well as the fixture representing the local ground.

After this, go to the **Weld Points** in the same window. The objective is now to weld together the parts Lower and Intermediate to the Superpart. It is not clear how much the choice of these weld points affects the results. However, it is most logical to follow the 3D PMI data for parts Lower and Intermediate as this describes how they are assembled in a vehicle (and therefore also a nominal buck), which in that case is 9 weld points.

4. Result

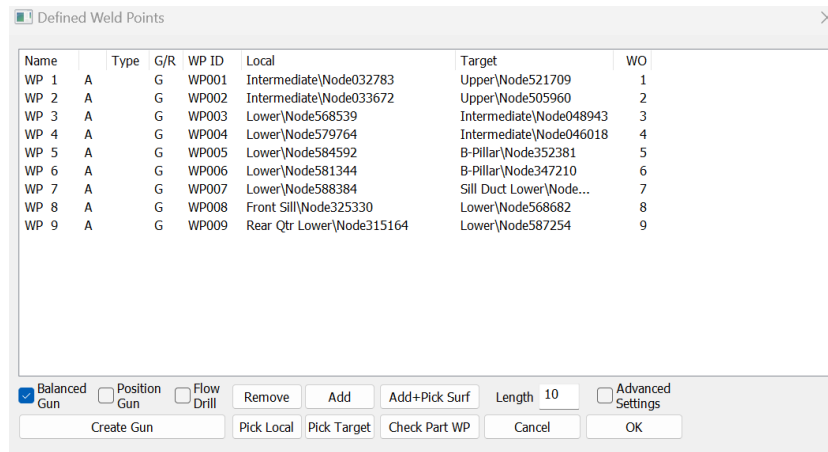


Figure 4.51: The defined weld points for connecting the superpart with the scanned parts.

Once the weld points are done, press **OK** to return to the initial assembly form. Now go to **Contact Points**. A new form then opens which us used to find contact points (see Figure 4.52).

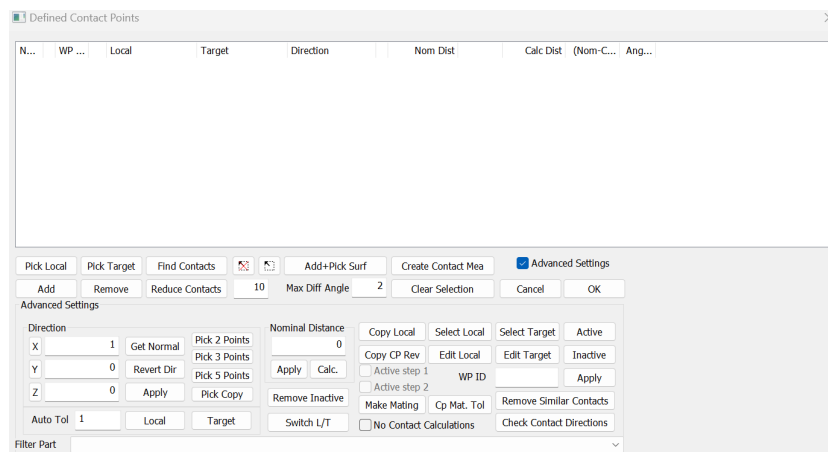
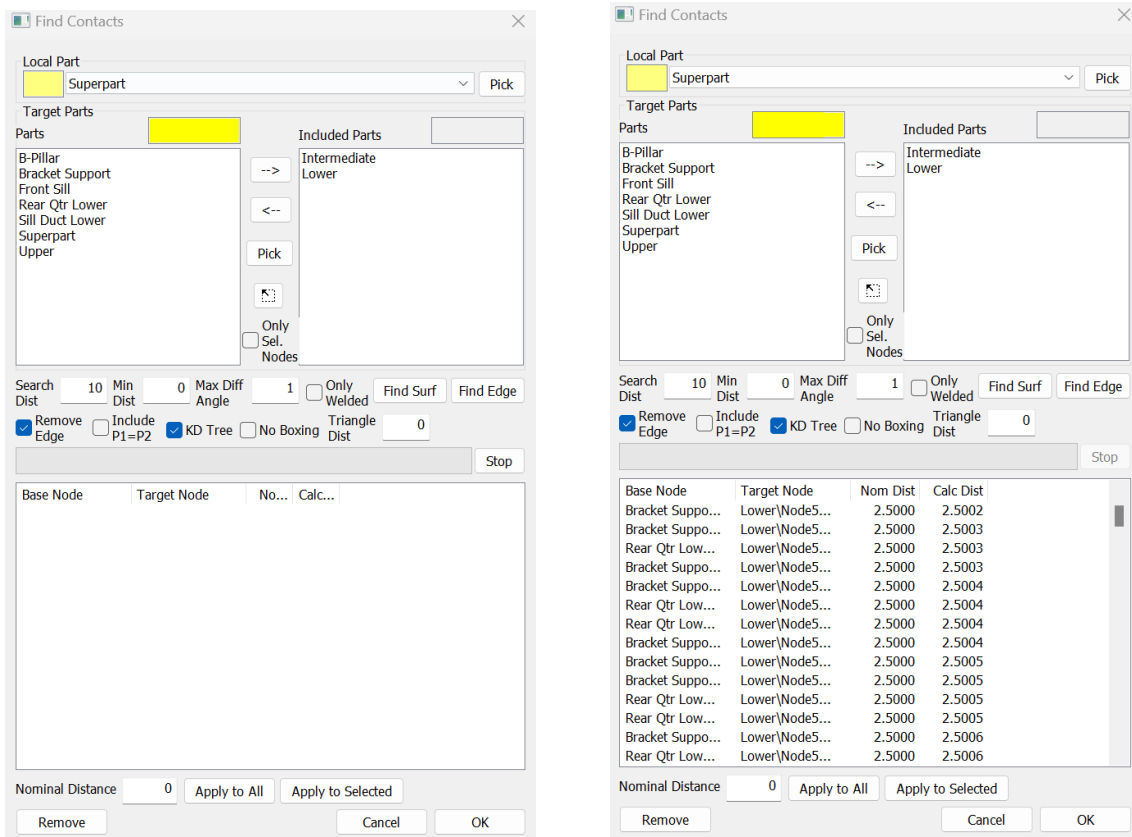


Figure 4.52: No contact points are defined yet.

As can be seen, there are no contact points at this stage. Next click on **Find Contacts**. A new window then appears that lets the user choose one local part, and one or several target parts. In this case, the Superpart is chosen as the local part and Intermediate and Lower are chosen as target parts. Then a search distance can be specified, as well as a minimum distance, which specifies within what range the software will calculate contact points. Whatever is of interest during the analysis can be chosen here. In this case the search distance is 10 and the minimum distance is 0 which are the initial values. The **Max Diff Angle** is not altered and has the initial value of 2 (see Figure 4.53a). Next the user can click on either **Find Surf** or **Find Edge** to find either surface or edge contact points. For this demonstration the contact between surfaces are of interest so therefore Find Surf is chosen. Once this is done, the software will calculate the contact points and they will appear in

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the initial list which can be seen in Figure 4.53b.



(a) The menu for finding contact points. The Superpart should be the local part, and Intermediate and Lower should be the targets.

(b) Newly calculated contact surfaces in the list.

Figure 4.53: The procedure of searching for contact points.

If one looks in the model window (without closing the find contacts tool), one can notice that there are red areas marked in the part window. These red areas are contact points (see Figure 4.54).

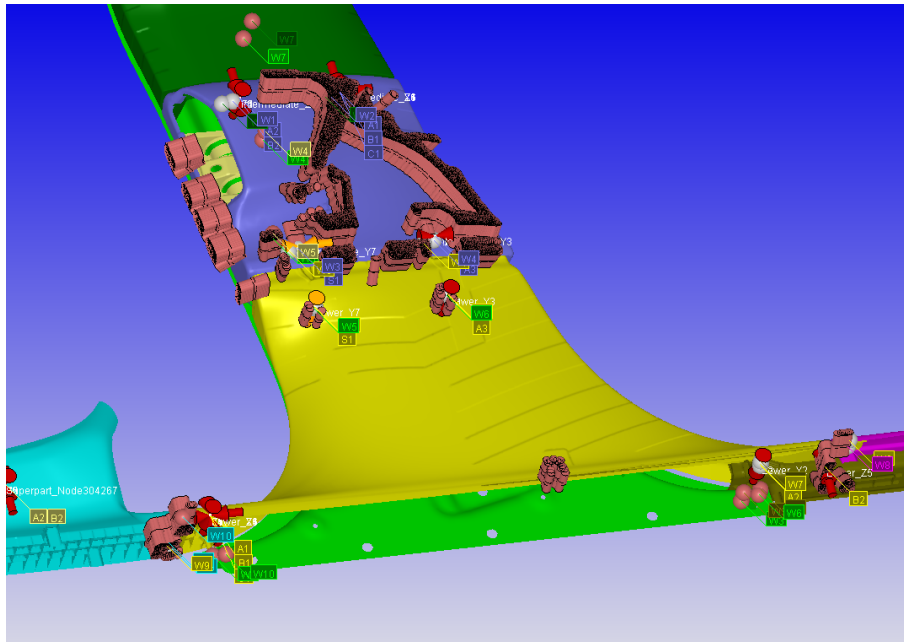


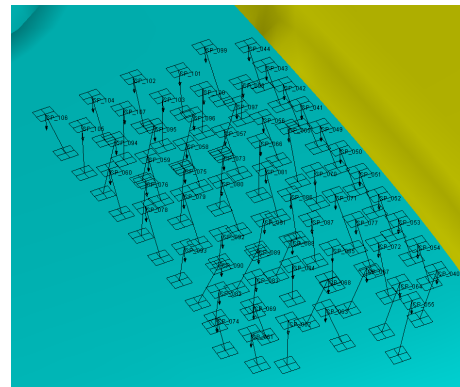
Figure 4.54: The marked red areas show where the surfaces have contact.

If the user presses OK, the marked red areas will disappear. Now the defined list of contact points will have these calculated contact points implemented. However, all of the contact points calculated with the **Find Surf** tool are not saved in the list. It depends on the difference between the nominal and calculated values, and the RD&T software then saves the most important points. A total of 150 contact points can now be found in the list, each one represents a contact between Lower and another part in the Superpart assembly (see Figure 4.55a). No contact points for Intermediate were saved. Each contact points tells in which local parts (a "surrounding" part in the Superpart) there exists a contact with a target part (Lower or Intermediate). It tells of the angle difference, nominal distance, the calculated distance from the scan data, as well as the difference between nominal and calculated values, thus showing the result of variation. Once the user presses OK and go to the **Handle Measures** button in the main toolbar, one can also notice that these contact points have now measures created on them. They can also be seen in the model window. Make sure that the button **Toggle Measure Visibility** is marked so the measures can be seen in the model window. Figure 4.55b demonstrates a few measures that tell of contact points between parts Lower and Rear Qtr Lower (Superpart).

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Name	WP ID	Local	Target	Direction	Nom Dist	Calc Dist	(Nom-C...)	Ang...		
CP 52	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.18, 0.98	A...	2.500	A	2.719	0.219	0.60
CP 53	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.18, 0.98	A...	2.500	A	2.702	0.202	0.50
CP 54	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.18, 0.98	A...	2.500	A	2.684	0.184	0.54
CP 55	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.10, 1.00	A...	2.500	A	2.723	0.223	0.64
CP 56	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.11, 0.99	A...	2.500	A	2.727	0.227	0.78
CP 57	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.16, 0.99	A...	2.500	A	2.740	0.240	0.90
CP 58	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.08, 1.00	A...	2.500	A	2.692	0.192	0.55
CP 59	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.08, 1.00	A...	2.500	A	2.672	0.172	0.58
CP 60	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.08, 1.00	A...	2.500	A	2.649	0.149	0.61
CP 61	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.14, 0.99	A...	2.500	A	2.727	0.227	0.83
CP 62	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.09, 1.00	A...	2.500	A	2.648	0.148	0.68
CP 63	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.09, 1.00	A...	2.500	A	2.670	0.170	0.62
CP 64	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.09, 1.00	A...	2.500	A	2.691	0.191	0.60
CP 65	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.09, 1.00	A...	2.500	A	2.711	0.211	0.54
CP 66	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.16, 0.99	A...	2.500	A	2.663	0.163	0.72
CP 67	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.16, 0.99	A...	2.500	A	2.682	0.182	0.63
CP 68	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.16, 0.99	A...	2.500	A	2.701	0.201	0.63
CP 69	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.13, 0.99	A...	2.500	A	2.717	0.217	0.56
CP 70	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.10, 0.99	A...	2.500	A	2.711	0.211	0.51
CP 71	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.13, 0.99	A...	2.500	A	2.714	0.214	0.50
CP 72	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.14, 0.99	A...	2.500	A	2.701	0.201	0.77
CP 73	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.14, 0.99	A...	2.500	A	2.679	0.179	0.71
CP 74	A	Rear Qtr Lower...	LowerNode55...	-0.01, 0.14, 0.99	A...	2.500	A	2.676	0.176	0.72

(a) Some of the contact points are now saved in the defined contact points list.



(b) Contact points between Lower and Rear Qtr Lower as measures.

Figure 4.55: The resulting calculated contact points.

f) Create measures of interest (Gaps, Flushes, Point Self, Parallelism, etc.)

Once the contact points have been found, one can also create measures in the model. These measures can then be used to analyze the variation in the scan data, and how this is visualized in the complete assembly. First go to **Handle Measures** in the main toolbar (see Figure 4.56).

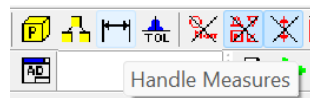
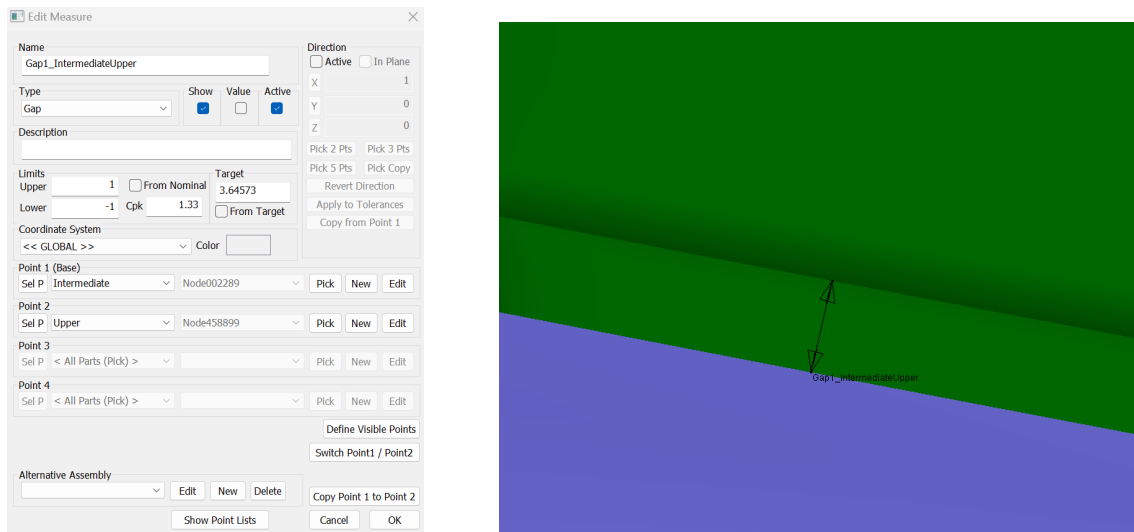


Figure 4.56: The Handle Measures tool.

After this the window of defined measures in the model should be open. If the contact points have previously been created as measures, these can also be seen in the list. The next step is to create all measures that are of interest during the variation analysis. It is often important to analyze gaps and flushes in a vehicle assembly, so therefore in this model many measures are imported for this. Figure 4.57a shows the creation of a gap measure between parts Intermediate and Upper (Superpart). Upper and lower limits can also be set according to preferences. The local and target points are selected by clicking on specific mesh nodes where the edges of each part should meet. Once all settings are set for the gap measure the user can press OK and the measure can be seen in the model window (see Figure 4.57b).

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(a) The definition of a gap measure.

(b) The gap measure between parts Intermediate and Upper.

Figure 4.57: Definition of a gap measure, an important type of measurement in verifying part geometries in a vehicle assembly.

Another often interesting type of measurement in a nominal buck is the parallelism between two measures, such as two gaps. When using two gaps the tool calculates difference between the two extracted gap values (located between the same two parts). Figure 4.60 demonstrates the creation of a parallelism measure, where two earlier created gap measures are included in the calculation.

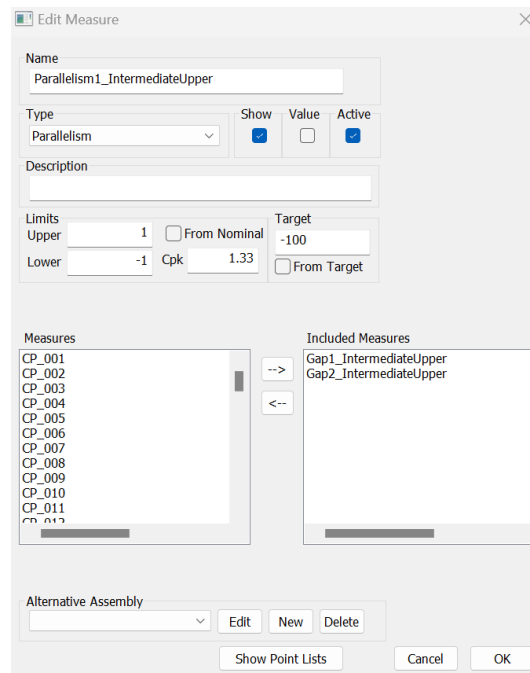


Figure 4.58: The creation of a parallelism measure.

Figure 4.59 also demonstrates where these two gap measures are located.

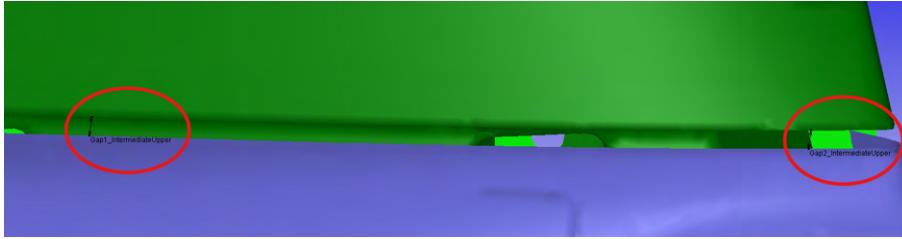


Figure 4.59: The two gap measures included in the parallelism measure.

The last type of measure of importance is a Point Self measure (see Figure 4.60). This type of measure only uses one point of a part, and calculates how that points varies between the nominal data and the scan data. A few of these are placed on the correct surface (the surface that earlier has been scanned) of parts Lower and Intermediate. It is also important that the **Active** box is marked under **Direction**, and that the direction corresponds to the normal direction of the surface of the picked point.

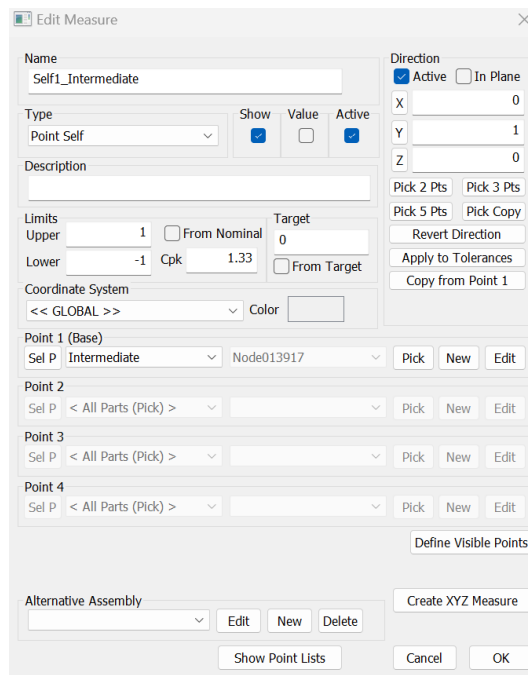


Figure 4.60: A Self Point measure.

Once all measures are created this step is complete. For the analysis of parts Lower and Intermediate, all measures in the list in Figure 4.61 were created.

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Name	A S V Type	Point/Arc 1	Point/Arc 2	Point/Arc 3	Point/Arc 4	Alt. Assembl.
CP_148	A.S..H..Point-Point	Rear Qtr Lower(Node31...	Lower(Node587118			
CP_149	A.S..H..Point-Point	Rear Qtr Lower(Node31...	Lower(Node587116			
CP_150	A.S..H..Point-Point	Rear Qtr Lower(Node31...	Lower(Node587115			
Flush1_IntermediateUpper	A.S..H..Flush	Intermediate(Node002297	Upper(Node458905			
Flush2_LowerIntermediate	A.S..H..Flush	Lower(Node509516	Intermediate(Node...			
Flush3_LowerFrontsill	A.S..H..Flush	Front Sill(Node285792	Lower(Node505489			
Flush4_LowerRearqtrlower	A.S..H..Flush	Lower(Node502673	Rear Qtr Lower(N...			
Gap2_IntermediateUpper	A.S..H..Gap	Intermediate(Node002289	Upper(Node458899			
Gap10_LowerRearqtrlower	A.S..H..Gap	Lower(Node502678	Rear Qtr Lower(N...			
Gap2_IntermediateUpper	A.S..H..Gap	Intermediate(Node001488	Upper(Node455580			
Gap3_IntermediateUpper	A.S..H..Gap	Intermediate(Node00702	Upper(Node185502			
Gap4_LowerIntermediate	A.S..H..Gap	Intermediate(Node003466	Lower(Node508530			
Gap5_LowerIntermediate	A.S..H..Gap	Intermediate(Node003416	Lower(Node509487			
Gap7_LowerIntermediate	A.S..H..Gap	Intermediate(Node003352	Lower(Node509520			
Gap7_LowerFrontsill	A.S..H..Gap	Front Sill(Node283008	Lower(Node511111			
Gap8_LowerFrontsill	A.S..H..Gap	Lower(Node510855	Front Sill(Node278092			
Gap9_LowerRearqtrlower	A.S..H..Gap	Lower(Node504346	Rear Qtr Lower(N...			
Parallelism1_Intermediate...	A.S..H..Parallelism					
Parallelism2_Intermediate...	A.S..H..Parallelism					
Self1_Intermediate	A.S..H..Point Self	Intermediate(Node013917				
Self2_Intermediate	A.S..H..Point Self	Intermediate(Node001239				
Self3_Intermediate	A.S..H..Point Self	Intermediate(Node023780				
Self4_Intermediate	A.S..H..Point Self	Intermediate(Node021919				
Self5_Lower	A.S..H..Point Self	Lower(Node563411				
Self6_Lower	A.S..H..Point Self	Lower(Node567408				
Self7_Lower	A.S..H..Point Self	Lower(Node556522				
Self8_Lower	A.S..H..Point Self	Lower(Node592879				

Figure 4.61: All measures used in the analysis of parts Lower and Intermediate

g) Perform a variation analysis

The last step is to perform a variation analysis. First the settings need to be changed for the analysis. Therefore go to **Miscellaneous**, then **Compliant Settings**. Then the Solver needs to be changed to most stable (see Figure 4.62).

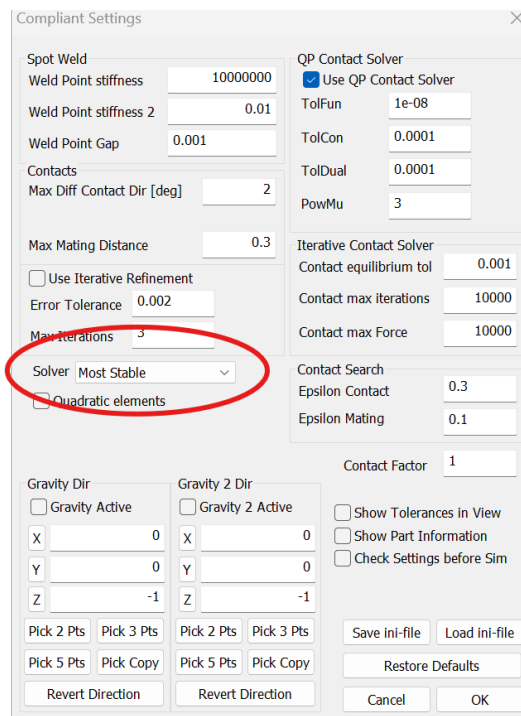


Figure 4.62: The solver should be set to most stable.

After this a variation analysis will be performed, therefore press the **Analyze Vari-**

ation button (see Figure 4.63).

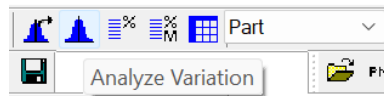


Figure 4.63: Tool for analyzing variation.

The software proceeds with calculating the variation. After a while another window pops up. Here **All Comb.** should be chosen, however it probably does not matter much if only the scan data is analyzed as it is only one tolerance for each part.

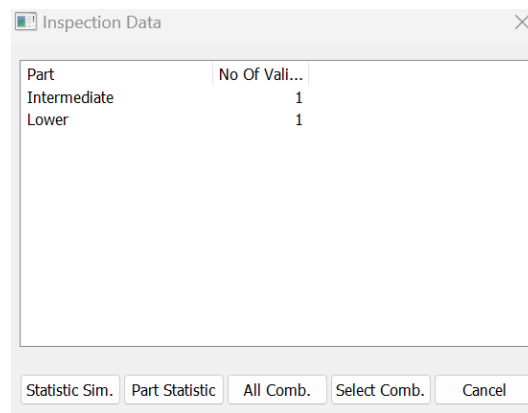


Figure 4.64: Inspection data window.

Once the analysis is completed, a new window will open up. This window gives the result of the variation analysis, showing nominal values compared to scan data values, in each one of the measures. There are no range or sigma values, but that is because there only one value for each measure. Thus it is actually not variation, but rather deviation that is being analyzed.

4. Result

Variation Results for LowerIntermediateVariationResults

All Measures Previous Next CP_001

Cpk Limits 1.33 Apply As Spec. Rel Abs As Spec. Sigma 8 Create CP Export Print All

Measure	Range	6 Sigma	8 Sigma	Nominal	Mean	Mean shift	Cpk...	Min LL	Max UL	L Out	U Out
CP_148	0	0	0	7.61	7.38	4.88	---	4.88	-9.88	0	0
CP_149	0	0	0	7.73	7.54	5.04	---	5.04	-10	0	0
CP_150	0	0	0	7.47	7.3	4.8	---	4.8	-9.8	0	0
Flush1_IntermediateUpper	0	0	0	3.69	2.49	-1.2	---	2.49	-2.49	0	100
Flush2_LowerIntermediate	0	0	0	4.75	4.07	-0.677	---	4.07	-4.07	0	100
Flush3_LowerFrontsill	0	0	0	5.67	4.41	-1.26	---	4.41	-4.41	0	100
Flush4_LowerRearqtrLower	0	0	0	3.36	3.52	0.159	---	3.52	-3.52	0	100
Gap1_LowerIntermediateUpper	0	0	0	3.69	2.58	-1.11	---	2.58	-2.58	0	100
Gap10_LowerRearqtrLower	0	0	0	3.14	3.12	-0.0233	---	3.12	-3.12	0	100
Gap2_IntermediateUpper	0	0	0	3.67	3.39	-0.28	---	3.39	-3.39	0	100
Gap3_IntermediateUpper	0	0	0	4.1	6.4	2.3	---	6.4	-6.4	0	100
Gap4_LowerIntermediate	0	0	0	4.76	4.98	0.224	---	4.98	-4.98	0	100
Gap5_LowerIntermediate	0	0	0	4.83	3.96	-0.868	---	3.96	-3.96	0	100
Gap6_LowerIntermediate	0	0	0	4.72	4.35	-0.375	---	4.35	-4.35	0	100
Gap7_LowerFrontsill	0	0	0	4.78	3.63	-1.15	---	3.63	-3.63	0	100
Gap8_LowerFrontsill	0	0	0	5.33	4.16	-1.17	---	4.16	-4.16	0	100
Gap9_LowerRearqtrLower	0	0	0	7.78	6.88	-0.9	---	6.88	-6.88	0	100
Parallelism1_IntermediateUpper 1/2	0	0	0	0.0204	-0.81	-0.831	---	-0.81	0.81	0	0
Parallelism2_IntermediateLower 1/2	0	0	0	0.11	-0.383	-0.493	---	-0.383	0.383	0	0
Self1_Intermediate	0	0	0	0	-0.592	-0.592	---	-0.592	0.592	0	0
Self2_Intermediate	0	0	0	0	0.156	0.156	---	0.156	-0.156	0	0
Self3_Intermediate	0	0	0	0	2.41	2.41	---	2.41	-2.41	0	100
Self4_Intermediate	0	0	0	0	0.603	0.603	---	0.603	-0.603	0	0
Self5_Lower	0	0	0	0	-0.132	-0.132	---	-0.132	0.132	0	0
Self6_Lower	0	0	0	0	0.13	0.13	---	0.13	-0.13	0	0
Self7_Lower	0	0	0	0	0.679	0.679	---	0.679	-0.679	0	0
Self8_Lower	0	0	0	0	-0.152	-0.152	---	-0.152	0.152	0	0

Sum 6 0 Min/Max Show Use MP Tol Min Max Norm 1

Export Filter Add. Mea for MP Tol R1 200 R2 200

Demand Vis. Toolbar

Figure 4.65: Results from the variation analysis for each measure.

One can also visualize this deviation as a color coding in the model. To do this, press OK in the results window, then go to **Part Variation Color** (see Figure 4.66). In the inspection data window that comes up, press All Comb. once again.

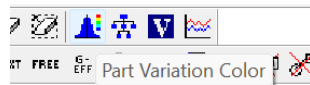


Figure 4.66: Tool for analyzing part variation by color coding.

Once the calculations are done, the model should be colored which visualizes the deviation. If no color coding is shown, make sure that the **Toggle Color-Coding** button is marked in the main toolbar. Then, one can double-click the color scheme in the top-right corner can be double-clicked which will open up the settings for the part variation. Here the **Mean color-coding** should be marked. Then the user can change to analyze deviation in a specific direction, or normal to see in all directions. The user can also set min and max values for the scale, or do an auto-scale which will make the software calculate the min- and max-values based on the values in the scan data. figures 4.67 and 4.68 shows the results of both cases, in Figure 4.67 the min- and max-values are set to -1 and 1, which shows large parts of Lower and Intermediate having variation under or above these values. This variation can therefore be problematic if these limits can not be exceeded. Figure 4.68 on the other hand, have auto-scaled values, which shows that most of the part geometries are within the green areas. Of course, the correct choice of scaling depends on the requirements regarding tolerances and geometries of each part.

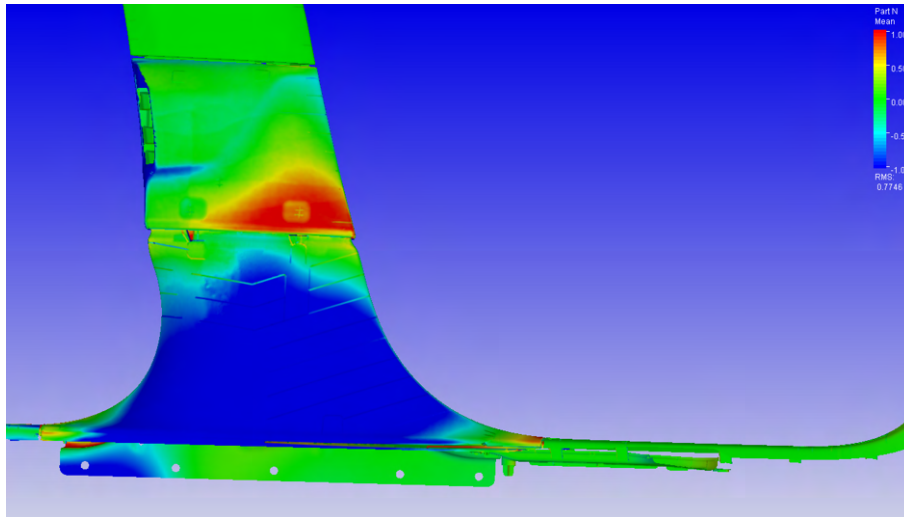


Figure 4.67: Color coding, min- and max-values of -1 and 1.

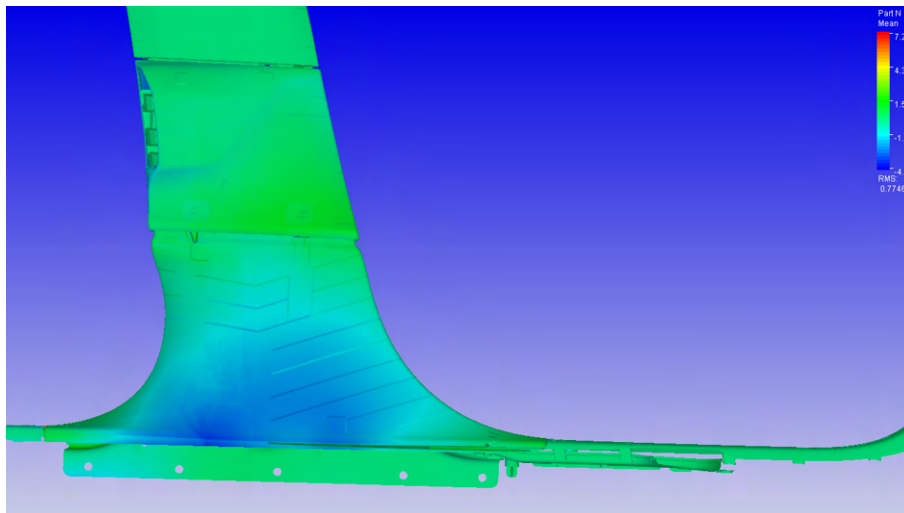


Figure 4.68: Color coding, min- and max-values auto-scaled to -4 and 7.

4.3.2.6 Output of Virtual Verification Method using RD&T

Once all steps are completed, the following results can be used to verify the part geometry:

- Contact points between parts and their nominal surroundings, showing how the deformed (scanned) part causes a contact (see Figure 4.55a and Figure 4.55b).
- Measures that show nominal and calculated (scan) values after the variation analysis, showing deviations in the scan data. These can then be compared to geometric part specifications regarding limits that can or cannot be exceeded (see Figure 4.65).
- A color coding for each part which visualizes the geometric deviation (see Figure 4.67).

4.4 Comparative Analysis: Physical versus Virtual Verification

Findings from the literature study & interviews, in combination with the demonstration in the case study, allow for a direct comparison between the physical contra virtual method - their benefits and drawbacks. Chapter 4.3.2 proves creating virtual models of real parts with geometrical deviations is entirely possible.

To justly compare them, different aspects will be analyzed and how the physical and virtual methods have either advantages or drawbacks within these aspects. The aspects included in the comparison are the following:

- Efficiency
- Accuracy
- Cost
- Sustainability
- Flexibility

4.4.1 Efficiency

The efficiency of the nominal buck process is defined as the speed and accuracy with which tasks associated with the nominal buck can be performed. These are design and manufacturing of nominal buck, part verification in nominal buck, fixture creation, and shipping.

Chapter 4.1.1 describe how the nominal buck is created and how parts are currently verified. This is a lengthy process that involve a wide range of engineers to function. It is time-consuming not only in the aspect of testing, but also when parts or the nominal buck need to be reconstructed to fit tolerances or aesthetics. Additionally, fixtures for part verification need to be designed, created and shipped from different suppliers around the world to the factory so repeatability and accuracy can be achieved.

A virtual simulation of the nominal buck process would make this considerably more efficient. First of all, the step-by-step guide can be accomplished by anyone. Parts can be integrated and tested in the simulation swiftly without much prior knowledge of the software or even geometry assurance as a whole. This means that acquiring the correct results will not be expertise bound. Variation simulations of production and part deviation can be performed quickly and analyzed in a matter of minutes. Simulating the assembly of identical parts with varying tolerances in the nominal buck is significantly more efficient, as the software visualizes how many assemblies fall within specified tolerance limits. In addition, the locating schemes for parts can be quickly altered for its best fit and minimum geometrical sensitivity. Fixtures can be created virtually, eliminating the need for design and shipping, greatly improving efficiency in project development since waiting and development times are

eliminated. Cementing the virtual efficiency even further is the ability to quickly and accurately measure gaps, flush and other measures of the virtual model wherever the developer wants without equipment such as CMM machines.

4.4.2 Accuracy

The accuracy of the method refers to the accuracy of verifying the geometries of the parts. Parts that pass through the current nominal buck are either within geometric tolerances and delivered to the next step which is the final assembly, or they do not pass due to unacceptable geometries and deviations which require the part to be reworked. Accuracy thus refers to if the method accurately asserts the correct state of the part. An important question throughout the project has been whether a virtual solution can effectively verify parts with the same accuracy as the current process.

First, it should be noted that a high degree of confidence was placed in the accuracy of the software tools used — specifically RD&T and PolyWorks — as well as the scanning equipment, to calculate the precise dimensions of the components analyzed in the case study. Due to the nominal buck being located in China, it was not possible to conduct direct comparative testing between the digital and physical methods. This represents a clear and significant limitation of the study. Nonetheless, all feasible precautions were taken to ensure the validity and reliability of the results (such as virtual fixtures to reduce risk of spring-back affect, creating detailed meshes, inserting correct material properties in simulation model, etc.).

Regarding the current physical process, it is straightforward and accurate. That is one of the strengths of the current method, as parts are inserted in a nominal environment with fixtures and measured directly using CMM probes and, if needed, specialized gauges, as well as other measurement tools. As it is a entirely physical process, there is no risk of virtual risks causing any errors in the accuracy of the result. The operator conducting these measurements can therefore see the results instantly after measurement, and note the results in the PIRA platform. However, because the results are dependent on the effectiveness of the operator, both in terms of correct insertion and accurate verification, there is a risk of human error. The accuracy of the method therefore depends on the prior experience and skill of the operator.

The accuracy of the virtual process depends on the accuracy of various files and steps. However, once some of the files have been created for each part, such as meshes and RD&T files containing CAD and positioning systems, those steps are finished and do not need to be re-done every time a verification needs to be conducted. The RD&T file containing the positioning system is based on 3D PMI data and is therefore very accurate according to product specifications and how the part is assembled in the vehicle. Making meshes can be a quite hefty and time-consuming process, especially with parts of complex geometries or with variations in the part

thickness. However if the mesh is successfully achieved with a small element size the meshes can yield highly accurate results in later simulations. During the simulations of the virtual fixture and virtual matching modules, many steps allow for a high degree of automation using data scripts as input to the software. For example, the most suitable sphere placement in the virtual fixture module for one part will always be the same. The only process that may be difficult to automate is the 3D scanning process. This requires an human operator performing the scan, which requires both skill and experience in order to yield an accurate result. As have been mentioned, virtual fixtures were used to collect data of the free state form of the part, thus also showing that the method was adapted to make it more accurate. The free state form catches the natural and realistic state of the part, without any risk of spring-back effect. The post-processing of the model, where scan errors are eliminated, also necessitates a skilled worker who understands which parts of the geometry that are crucial to retain. However, with further development on this topic, there are no great barriers preventing the 3D scanning process and post-processing of scan to be automated as well.

4.4.3 Cost

The cost can be defined as the total cost, including tools, equipment, and personnel, that is spent on performing the geometry verification processes.

The current nominal buck process is quite costly for many reasons. Fixtures to enable measuring for different parts in the nominal buck need to be designed and manufactured, creating a personnel and material cost. These fixtures also need to be transported from the manufacturer to the factory in Chongqing which also costs a significant amount (the exact numbers of these costs could unfortunately not be obtained). As discussed earlier in chapter 4.1.1, both the nominal buck itself and the part manufacturing pose an economical challenge for Polestar. It is evident that these also need to be transported from the supplier to the factory which adds to the total cost. The cost of fixtures and the nominal buck for Polestar 5 was 4.78 million SEK. This is without the cost of logistical processes (where as the exact costs of logistics unfortunately could not be acquired). There is also the question of personnel costs. Currently, around 50 employees are directly involved in the design, testing, manufacturing and verification of the nominal buck. Assuming the salary is 57 200 SEK for each employee, which in 2023 was the average engineer salary in Sweden (SverigesIngenjörer, 2023), the total monthly cost of the workforce is 2.86 million SEK. If it takes 3 years from first design to completed functional car, the cost totals 102.96 million SEK. Finally, to measure all parts of the nominal buck, industrial CMM machines and 3D scanners are necessary which add additional costs.

Switching to a virtual verification process can lead to substantial cost reductions. First, physical fixtures are no longer required, as they can be created virtually in RD&T. Similarly, the nominal buck and all but one physical part used for testing become unnecessary, since accurate simulations can be performed in RD&T.

This eliminates the need for a physical buck, most of the test parts, and fixtures altogether. As a result, logistical challenges, such as transportation costs, are also eliminated. Regarding workforce expenses, while most R&D engineers are still essential during the early stages of the project, their involvement in later phases is significantly reduced, leading to notable labor cost savings. One essential component for enabling virtual verification is 3D scanning equipment, which is critical for capturing realistic surface scans of parts. Ideally, the supplier already has access to a 3D scanner. Selecting a supplier with this capability falls under the responsibility of the contract manager in China. Consequently, the need for additional CMM equipment and separate 3D scanning resources is also removed from the Polestar factory. The new cost that will be necessary is the expenditure of licenses like RD&T, salaries to the engineers who will work with digital verification, as well as training programs so the workers have the required knowledge to do these tests correctly.

4.4.4 Sustainability

When judging the sustainability of the process there are several factors that are important to consider. Sustainability can involve anything from the extraction of minerals for parts to the final product in use. In this case however, the sustainability is focused on the impact of produced parts and transportation of these.

The physical process entails that several test parts are produced for measuring and inspection. The amount of parts required vary depending on the historic accuracy of the part but can amount to anything between 1-50 as mentioned in 4.1.1. Additionally the nominal buck needs to be produced and often times altered which impacts its sustainability. Finally, said parts and nominal buck need to be transported from suppliers to factory. The transportation in itself can impact the sustainability differently depending on how they're transported. Since all manufacturers reside within China, its assumed everything is transported using trains or trucks.

Using software to simulate the nominal buck as a whole removes the need for producing more than one part and the need for transportation of parts. Consequently, the steps that negatively impact sustainability in the physical process are eliminated.

4.4.5 Flexibility

Flexibility refers to the ability of a process to accommodate changes in design, production requirements, or verification methods with minimal disruption. In the context of geometry assurance, this means how easily the verification process can adapt to new vehicle models, part modifications, and process innovations.

The physical verification process using a nominal buck offers limited flexibility. Once the buck and its associated fixtures are manufactured, they are specific to a single vehicle model and its initial design state. If design changes occur, the nominal buck

often needs to be re-machined or, in extreme cases, returned to the supplier for modification. This rework introduces substantial delays, ranging from one to three months, and adds both cost and complexity to the development timeline. While minor on-site modifications such as grinding are sometimes possible, these adjustments are limited and depend heavily on technician skill and availability.

In contrast, the virtual verification process provides a significantly higher level of flexibility. Using simulation tools such as RD&T, updated CAD data can be incorporated quickly, enabling the verification process to continue without physically modifying anything. New scenarios can be simulated with minimal effort, including tolerance changes, part replacements, or the evaluation of new fastening solutions. This adaptability is particularly valuable during early development phases when design iterations are frequent.

Furthermore, the virtual method supports parallel development. Multiple design alternatives can be completed simultaneously, which is not feasible with the physical buck. This enhances cross-functional collaboration, as teams across departments and even countries can access and contribute to the same virtual model in real time.

However, virtual flexibility still has its challenges. The effectiveness of the process depends on the companies virtual infrastructure, including up to date CAD models, correct scan data, etc. In addition, the organization must establish clear procedures and standards for work processes and data handling to prevent version control issues.

4.4.6 Summary of comparison

To clearly depict the advantages and disadvantages which have been put forth in this chapter, a summary Figure is displayed below, containing both the physical and virtual process (see Figure 4.69).

Category	Physical Process – Advantages	Physical Process – Disadvantages	Digital Process – Advantages	Digital Process – Disadvantages
Cost	Familiar process with existing infrastructure Fixtures can be reused for multiple builds	High manufacturing cost of nominal buck (~5M SEK) Expensive to implement major design changes Labor-intensive and repetitive	Lower long-term costs Eliminates repeated buck builds Reduced material and transport needs	Requires initial investment in software and hardware Setup of digital workflows and user training needed
Accuracy	High physical accuracy in controlled settings Allows tactile and visual inspections	Risk of manual measurement error Fixture misalignment possible Inconsistent simulation of flexible parts	Simulation of non-rigid behaviors Dense data capture from 3D scans	Sensitive to scan setup and angles Scanning can be difficult and sometimes miss important deviations
Efficiency	Well-established and understood workflow	Manual assembly and disassembly is time-consuming Bottlenecks during large batch testing or changes	Faster verification once set up Automated analysis and report generation Enables testing of multiple scenarios in parallel	Initial setup and training takes time Requires interdepartmental coordination
Sustainability		High material use to create parts/fixtures Shipping of physical buck, parts, fixtures Reworks often needed	Reduces material waste significantly Fewer shipments and physical prototypes Easier traceability and digital documentation	
Flexibility	Technicians can make minor adjustments manually	Limited adaptability to design changes Revalidation is slow and costly	Easily adaptable for different scenarios and iterations Quick to update and re-run simulations Remote collaboration is possible	Dependent on software stability and compatibility

Figure 4.69: Advantages/disadvantages with physical and digital nominal buck process.

Using this simplified visual of the advantages and disadvantages, parallels can be drawn to the quantitative results in Chapter 4.2. As can be extracted from this chapter, a digital simulation model significantly improve several aspects of the nominal buck process. This is in line with the question "If you currently measure and verify products physically, do you think digital tools would be beneficial for you?" which 93% of respondents agreed with. Even though this is the case, only 20% of the

same companies had implemented digital tools while 40% are in the early stages of implementation and an additional 33% considering implementation. This analysis shows that the industry knows the importance of using digital tools.

Three key disadvantages found with adopting a digital process are its high initial investment, the lack of expertise within companies to effectively implement it, and resistance to change. This is reflected accurately in the quantitative results question "What do you think is the biggest barrier to digitalizing your company's geometry verification process?" where answers amounted to 32% - high costs, 21% - lack of knowledge or expertise, and 16% - resistance to change within the company.

One question focused on the ergonomical aspect of the physical nominal buck. In some industries where the operators need to handle large parts, such as the automotive, manually assembling and disassembling parts seem to have a negative affect on the body. When asked if the industry found the physical verification process demanding in the interview, 54% answered yes or unsure, which correlates to this statement. In which case, eliminating the physical process would undoubtedly improve ergonomics.

Continuing to the sustainability aspect of the analysis. A digital process was found to significantly improve sustainability by reducing material waste, fewer shipments, and physical prototypes, as well as improving traceability and digital documentation. The quantitative results support this since 87% answered that a digital method could lead to either significant or slight reduced waste. Finally, an open question about what a digital verification process would improve the most overall was posed. Here, two categories stood out above the rest, these being 32% - increased efficiency and 30% answering reducing cost.

Summarizing, the industry has an accurate picture of how a digital geometry process could improve operations and companies as a whole. Furthermore, the barriers that they face to conduct the necessary implementations are known. This points to future projects which aim to implement digital solutions could become easier. Additionally 93% thought that a digital process would be beneficial. Despite this, only 20% of companies have implemented the tools mentioned above while 40% have started but are in the early stages of implementation. This could possibly point to the fact that the organization is resistant to change as previously presented. Companies know that a digital solution would improve operations but the change is not made. This analysis and parallel made to the quantitative results hope to bridge this gap and prove its usability to readers.

4.5 Impact of Virtual Implementation

By implementing a virtual software like RD&T to simulate the nominal buck process, it is concluded that the physical nominal buck is no longer needed. A virtual simulation of the nominal buck offers the same, if not better, accuracy, flexibility,

efficiency and sustainability as well as lower cost. The nominal buck will no longer be needed since the nominal CAD can be used for simulation. Interior and exterior parts which are tested in the nominal buck still need to be produced but not in the same amount as before. The most important factor that is extracted from a manufactured part is its realistic shape deviation from a nominal part. This enables engineers to analyze part deviation from nominal shape and the parts fit in its environment. Furthermore, the part can be compliantly simulated, which gives an idea of how the part will be deformed in relation to its assembly, with forces applied, such as gravity, and its contact with other parts and deviations in relation to these factors. Furthermore, using virtual fixturing, fixtures can be quickly created in the software, making the process faster and more cost-effective. Ultimately, only one part should be needed to simulate a realistic part in the simulation software. This is because, like in the case study, variation simulations that depend on the parts tolerances are used, effectively displaying several parts deviation in the final result. The measuring in the digital process is also much more efficient compared to the traditional physical process, requiring only a few clicks to be performed.

Another effect of this digitalization is that a substantial part of Polestar’s current nominal buck work flow can be completely removed or altered. It has been concluded from this thesis that the physical nominal buck is no longer needed. This means that the manufacturing part of the nominal buck creation workflow can be removed. This eliminates seven steps from the nominal buck development process, making it much faster and more efficient. Steps that will no longer be necessary are marked in the red area displayed in Figure 4.70.

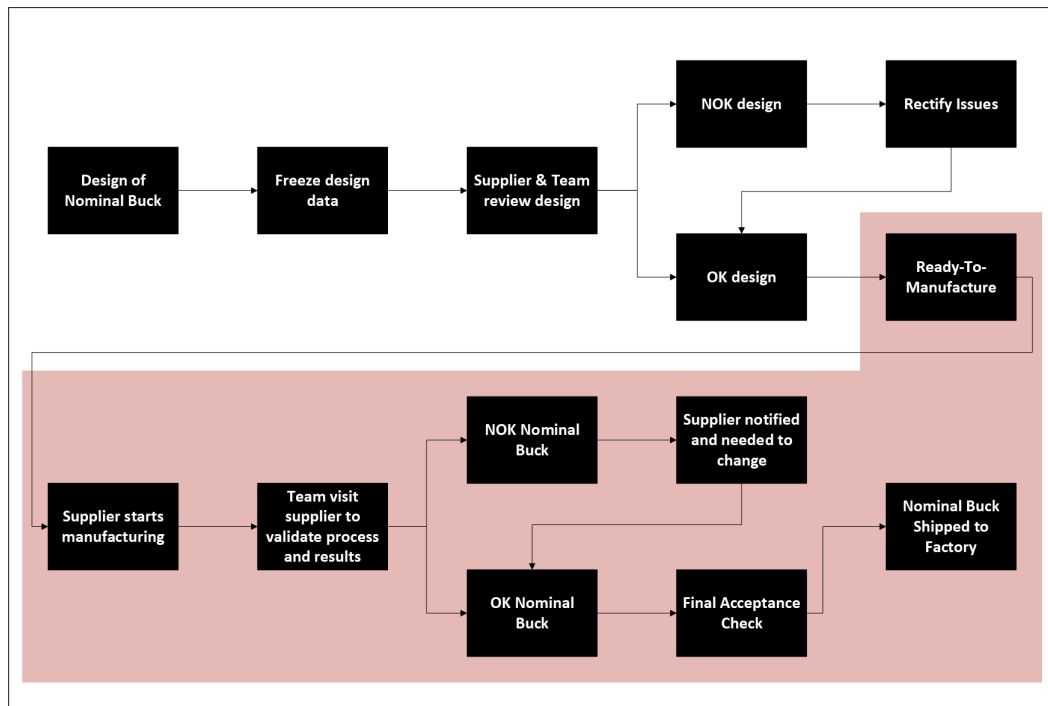


Figure 4.70: Steps eliminated in virtual nominal buck process.

The part verification in the nominal buck will also become entirely virtual but the steps which are shown in Figure 4.2 will remain the same, with the exception of physical measuring processes which will be performed digitally in the software. Additionally, instead of parts being sent to the factory for physical mounting and measuring, the parts should be scanned by the supplier and sent to the factory for virtual analysis. Ensuring suppliers have scanning capabilities or supplying them with equipment for scanning is therefore essential for the new process.

Conclusively, accounting for the changes made in both the nominal buck and part verification processes, a new workflow can be constructed for the virtual geometry assurance process. This workflow combines both processes while eliminating unnecessary steps and improving efficiency throughout the company's geometry assurance processes. The new virtual geometry process can be seen in Figure 4.71.

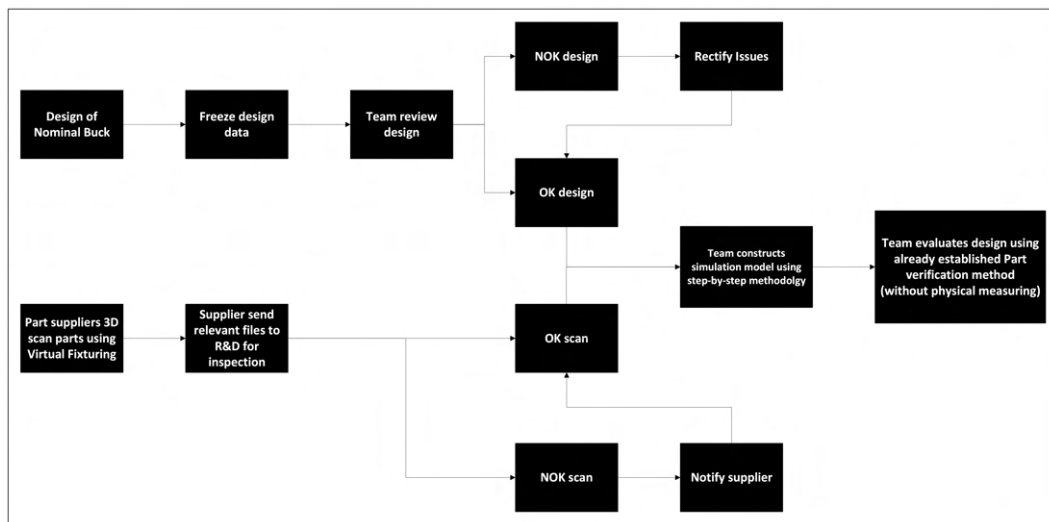


Figure 4.71: New virtual assurance process workflow.

4.5.1 Implementation Feasibility

The goal of the implementation feasibility is to assess how realistically the virtual verification software and its associated processes can be integrated into Polestar's existing workflows, organizational structure, and technological infrastructure. This includes identifying potential barriers, required resources, and change management considerations.

Creating the virtual framework to enable the implementation of this work process can seem like a monumental task, especially for a company as large as Polestar. When a working structure is already established in a company, remaking the process and integrating several different virtual softwares poses a substantial challenge. Companies are often met by organizational challenges such as workforce resistance, budget constraints and lack of expertise when such a restructuring occurs. This is also in line with the results regarding potential barriers from the quantitative re-

sults in chapter 4.2 and Figure 4.8. Even though such workforce resistance exists, it may not necessarily mean that an implementation of digital tools is negative for the company, rather just that the workforce is worried about their role in such an implementation. A important aspect is therefore to retain continuous communication with the workforce.

If the step-by-step process is put in the limelight, it is clear that it is not a difficult process to perform. Especially if all steps and tasks are structurally allocated to certain departments of the company. During this thesis, two master students with little to no prior knowledge of RD&T managed to create an accurate virtual model. This despite not knowing where to find the needed information or Polestar having an established virtual framework for acquiring the specific files in a easy manner. This entails that a company with a structured work method will be able to do it more efficiently and accurately.

In broad strokes, there are three steps necessary to enable a transition to a virtual geometry verification process. These steps are the following:

- The initial step in the transformation involves developing a centralized virtual platform where all essential files, such as meshes, point clouds, and CAD models, can be accessed and managed. This platform could mirror Polestar's existing virtual environment, the Active Workspace, in both structure and usability. By linking relevant files directly to parts through the nominal design, the system consolidates all data in one location, providing a clear and intuitive hub for employees to retrieve and store part related information.
- Secondly, change management must be strategically planned. As highlighted in interviews, the current process is deeply rooted in physical validation, forming both an operational routine and a mindset. Introducing virtual tools may be met with resistance unless clear benefits, such as time and cost savings, are demonstrated early on. Moreover, a sudden shift to a fully virtual method may hinder adoption, as employees could feel overwhelmed by the scale of change, potentially affecting morale. Therefore, a gradual transition is essential, giving both the organization and its workforce the time to adapt and fully integrate the new approach.
- Following this, employees need to undergo basic courses in navigating RD&T and how to interpret results from different tools that are used. This will be crucial in realising the full potential of the virtual method. To simplify this process, PE Geometry, the company that co-develops RD&T with the Wingquist Laboratory or companies similar to it, can be engaged to deliver training courses.

Finally, interdepartmental collaboration, especially between the R&D department in the UK, the ME department in Gothenburg, and manufacturing in China, needs

to be formalized to ensure seamless communication and data flow. Communication tools and file-sharing systems may need updating to avoid issues such as unit conversion errors or misinterpretation of results.

4.5.2 Automation of Process

Automation is a key enabler in the transition from physical to virtual geometry verification, offering the potential to significantly reduce manual effort, minimize human error, and streamline repetitive tasks. In the context of Polestar’s nominal buck verification process, automation can be implemented at several stages of the virtual workflow, each contributing to improved efficiency, traceability, and scalability.

One of the most impactful areas for automation lies in data acquisition & pre-processing. As described in chapter 2.5.2, virtual fixturing begins with scanning physical parts to create virtual point clouds. This process, when done manually, is time-consuming and operator-dependent. However, by integrating automated 3D scanning systems, mounted on articulated arms or automated fixtures, scanning can be conducted in-line or at dedicated quality stations during early production phases. Some factories, as noted in interviews, have already begun using real-time scanning data to automatically align components like windshields. This demonstrates the growing maturity and feasibility of automated scanning in automotive environments. Even if this technology is very new and still being researched in order to reach its full potential, the possibilities of it are substantial.

Once the scan data is acquired, automation can continue through scripted processing of point cloud data into usable formats (e.g., CSV, STL, or DMIS files), and direct integration with simulation software such as RD&T. This eliminates manual conversion errors and ensures consistency across datasets. Software such as PolyWorks can be used in combination with custom scripts to automatically align and clean segments, enabling easy import into RD&T.

Beyond technical analysis, automation can be extended into report generation, ensuring that results from virtual verification are automatically formatted. These could then be automatically shared across departments, making development processes faster and more cooperative. This could include integration with systems like PLM platforms to create an uninterrupted flow of information from design to manufacturing.

5

Discussion

This chapter discusses three primary aspects of the study. First, it addresses the research questions outlined in the introduction. Second, it examines the challenges encountered and the limitations faced during the research process. Finally, it offers recommendations for future work to build upon and extend the contributions of this thesis.

5.1 Interpretation of Results

This chapter aims to answer the research questions which was posed in Chapter 1.5 by using the results achieved. First, the technological questions are answered, and then the sustainability questions.

5.1.1 Technological and Economical Research Questions

RQ1

What are the advantages/disadvantages of simulating nominal buck geometry assurance within a virtual space like RD&T?

There are numerous advantages and disadvantages with simulating the nominal buck process within a virtual space like RD&T. Chapter 4.4 aims to depict these using five crucial aspects - namely efficiency, accuracy, cost, sustainability and flexibility. Furthermore, using the aspects, it tries to effectively weigh them against each other in an effort to convey the best solution to the reader.

From that analysis, it has been conceived that the virtual method has many advantages - such as reduced lead times, lower material consumption & environmental impact, increased process flexibility, and enhanced data traceability. However, the challenges also need to be addressed - such as software limitations, implementation complexity, and required changes in Polestar's current workflow and skill sets, which could be difficult to realize.

RQ2

How do you ensure the most realistic simulation for nominal buck verification?

To ensure the most realistic simulation of a virtual nominal buck process, the case

study was devised. Using the steps shown in the case study, the model constructed will be as realistic as possible. Additionally, the case study creates a standardized way for Polestar and other stakeholders to follow when trying to construct their own digital models. In addition to this, several factors need to be considered. The scanning of parts need to be correctly and accurately performed each time. Also, creating scanning setups which can be quickly and efficiently readjusted for new parts are key in achieving a good result. If the utmost quality of these properties are not ensured, the precision of scanning quality will be compromised. Therefore, a small error in the beginning of the process can render the result worthless.

Additionally, how detailed the meshes are and what material properties the meshes are assigned are crucial. If the correct meshes are not used and post processing of said meshes are not up to par, the result of the simulation is put at risk. Using meshes which are not representative of the realistic part will, of course, give a skewed result. Another critical component to ensuring a realistic result is assigning meshes with the correct properties. These include elastic modulus, thickness, Poisson's ratio, etc. Data sheets for each part should therefore be acquired from supplier and used as input data to meshes accordingly.

RQ3

Can all parts be effectively simulated using a virtual nominal buck?

Yes. Based on the results found in this thesis, all the parts in the nominal buck can be effectively simulated virtually. On the other hand, only two plastic components that did not have exceptionally complicated geometries were simulated. Furthermore, the components in question were especially thin. These properties made it possible to make assumptions that made the modeling easier. As such, when simulating components with considerably thicker thicknesses and more complicated geometries, this might not be the case. This needs to further researched, as mentioned in Section 5.3.

RQ4

How would a transition to virtual geometry assurance impact Polestar?"

Based on the findings, a shift from physical nominal buck testing to digital simulations would bring several benefits.

- **Cost and Material Reduction:** The digital process would eliminate the need for physical prototypes, reducing material costs and waste associated with manufacturing the nominal buck. The reduction of waste also sustains the company's sustainability initiatives.
- **Efficiency Improvements:** Virtual verification processes, especially when automated, can speed up the testing and validation of parts, reducing lead times compared to physical testing. This can improve overall production efficiency.

- **Accuracy and Flexibility:** Virtual testing allows for more precise control over measurements and variations. Simulation tools can offer more flexibility in testing different scenarios and adjusting parts virtually before any physical alterations are made.

Overall, the transition to virtual geometry assurance would be a promising development for Polestar in terms of cost reduction, efficiency, and sustainability. However, successful implementation would require overcoming challenges such as resistance to change and integration of new digital workflows.

5.1.2 Sustainability Research Questions

RQ5

How would waste be reduced by digitalizing the nominal buck verification process?

Digitalizing the nominal buck verification process significantly reduces various forms of waste, both material and non-material:

- **Elimination of Physical Prototypes:** Manufacturing a physical nominal buck is resource-intensive, involving materials like aluminum and requiring complex fixtures. By digitalising the process, the need for fixtures and duplicates of the same parts are removed.
- **Reduced Rework and Scrap:** In the current physical process, design flaws or misaligned fastener placements often require part or buck reengineering. This leads to scrapping of parts or re-machining fixtures, both significant sources of material waste. By replacing this with virtual simulations in RD&T, these material and production costs are completely eliminated, reducing waste associated with creating and potentially reworking physical bucks. Virtual simulations allow these issues to be detected and corrected early in the design process, minimizing rework and waste.
- **Less Iteration Cycles:** Physical testing requires multiple iterations of part fitting, measuring, and disassembly, often repeated across 10–50 parts per build phase. Digital tools streamline this by enabling rapid virtual iterations, which reduces time, labor, and the wear-and-tear (and hence waste) of physical measuring devices and components.
- **Lower Transportation and Logistical Waste:** Physical bucks and parts are often shipped between suppliers and factories (e.g., between China and Sweden), generating emissions and packaging waste.

Digital workflows drastically reduce the need for international transport of physical components, leading to lower waste across the supply chain.

RQ6

How would employees working with nominal buck verification be impacted by digitalizing the nominal buck process?

Digitalizing the nominal buck verification process would lead to significant changes in the work of employees. The current process is highly manual and labor-intensive, requiring engineers and technicians to repeatedly assemble, measure, and disassemble components, sometimes up to 50 times per part. This not only consumes a great deal of time but also places physical strain on workers, as many tasks involve ergonomically demanding movements such as bending and reaching into awkward positions. Transitioning to a digital process would eliminate much of this repetitive manual labor, thereby improving efficiency and significantly reducing the physical burden on employees.

In addition to reducing manual workload, digitalization would alter the skills required from the workforce. The implementation of virtual tools such as RD&T, along with 3D scanning technologies, introduces a need for technical competencies in software use, data handling, and simulation-based verification methods. This would necessitate training among staff. While such a transition may be beneficial in the long term, it could also face resistance, especially from employees who are accustomed to the existing workflow. Change management will therefore be essential to ensure acceptance and smooth adoption of the new digital methods.

Furthermore, as the digital verification process becomes more robust and integrated early in the development phases, the need for engineers and technicians to be physically involved in later stages of the process could diminish. This shift may lead to a reduced demand for hands-on personnel during verification, potentially affecting job roles and workforce planning. However, it also opens up opportunities for increased collaboration across departments and geographical locations, as digital models can be shared and analyzed remotely. This improved accessibility could enhance flexibility for employees and streamline communication between teams in Sweden, the UK, and China.

Overall, digitalizing the nominal buck verification process would transform the nature of employees' work from a physically demanding and repetitive role to one that emphasizes digital proficiency, simulation expertise, and cross-functional collaboration.

5.2 Implementation Challenges & Constraints

During the thesis, several challenges were encountered, both technical and organizational. As a cause of this, certain constraints were assumed to arrive at the best possible result.

The most prevalent difficulty was the lack of a standardized method for how to construct a simulation model as well as the prerequisite files required for the simulation. There exists literature, specifically from the Wingquist laboratory group, on what preparatory work is required to create certain simulation models. Even if this is the case, there currently is no specific elaborate guide on exactly what files are needed, how to acquire said files, and steps for creating a digital simulation in RD&T. Thus, through interviews, literature study, and internal conversation with researchers, the process of conducting adequate preparatory work was devised to do everything needed. As the process was produced using what could be called a "mash-up" of software and technology that was available, it is not certain that it is the most optimal approach, just a possible method.

Another challenge was part material and geometry. In RD&T it is possible to define E-modulus, Poisson's ratio, part thickness, etc for compliant parts. This is in itself a crucial feature for creating compliant simulations that can imitate real world results. The problem was that not much prior research had been conducted in simulating plastic parts. Because of this, the work method was not clearly defined which made the imagined result unclear. Additionally, if parts have complicated geometries that include complexities like structural ribs, the meshing of the part becomes complicated. Meshing tools get confused how to mesh these sections, often times requiring extensive post-processing which also was the case. In addition to this, in contradiction to chapter 2.5.3, the plastic parts meshes were not volume meshes, but mid-meshes. In the end, satisfactory meshes of the parts were created that worked in RD&T. The meshes were given the same E-modulus, part thickness and Poisson's ratio according to the intermediate part because the data sheet for the lower part could not be acquired.

During the case study, several other constraints were also made. That is, regarding how the simulation was constructed. For example, both the intermediate part and lower part are actually both sub-assemblies composed of one outer and one inner part each. Instead of creating two meshes for the shells and assembling them, only mid-meshes of the inner parts were generated and analyzed. This is because using two meshes does not have a great deal of prior research and the result would be unclear. Therefore, an assumption was made that the outer shell of the part does not have any structural impact since in reality it is only a very thin fabric film, allowing for the use of mid-meshes instead of volume meshes.

A final constraint was made regarding the construction of the "Superpart" in the simulation model. The Superpart is an assembly consisting of 6 meshes that are connected to the intermediate and lower part mentioned in 4.3.2. Most of the parts included in the Superpart are plastic, but a constraint was made that said parts are steel. The cause of this is that only deviations of the intermediate and lower parts are relevant in this case. Therefore, the Superpart assembly should be as close to the nominal and rigid structure as possible. Making the parts E-module correspond to steel with extra reference points simulates a rigid nature of the Superpart.

5.3 Recommendations for Future Work

While this thesis demonstrated the feasibility and potential benefits of transitioning toward a digital nominal buck verification process, several areas remain open for further investigation and refinement. The following recommendations are proposed for future work:

- A key area for future work is the simulation of plastic components within virtual geometry assurance processes. Plastic parts introduce a different set of challenges due to their complex material behaviors and often complicated geometries. These components, commonly used in vehicle interiors, often include design features such as snaps, ribs or clips that behave in highly non-linear ways under load. As mentioned in the earlier chapter, several assumptions were made to perform the case study for plastic parts.
- Another recommended area for future work is the development of a fully or semi-automated process. Throughout this thesis, several steps in the workflow, such as scan data preparation and virtual fixturing and the entire simulation were carried out manually. While this worked for demonstration purposes and creating a step-by-step guide, this manual approach can result in inconsistencies and relies heavily on the user. Even though the process is not especially difficult, automating it would still eliminate potential errors. Automation could include coded scripts that perform all necessary steps in the correct order automatically. If the objective for a automotive mass manufacturer such as Polestar is to implement this digital method, automation is necessary.
- Furthermore, one big limitation during this project has been that the nominal buck has been located in China, making it impossible to do any tests. For example, it would have been greatly beneficial to analyze if all steps during the case study has led to the correct calculations of geometric deviations. This could have been analyzed easily if the parts could have been measured in a physical buck, which would have allowed for a direct comparison. A suggestion for future work is therefore to compare the two methods in detail.
- Lastly, a subjective recommendation is made regarding the visualization of 3D scanned results in the RD&T software. Currently, deviations from the nominal to the scanned part is visualized by color coding on a nominal mesh. Additionally, color stickers can be used to show the exact deviation in certain nodes. Even though this is the case, creating a function to visualize the scan cloud as a geometry is advised. This would make it much easier to quickly see the deviation of the part and assess its fit in the nominal environment, which is an important use in the current physical nominal buck process.

6

Conclusion

This thesis explores the feasibility of transitioning from a physical to a digital nominal buck verification process at Polestar, using the geometry assurance tool RD&T. The study explored subjects like improving efficiency, flexibility, and sustainability in Polestar's product development processes, particularly in the verification of fit and alignment of interior and exterior components.

Through literature review, industry interviews, and a focused case study, the research demonstrates that a virtual verification method, centered around 3D scanning, virtual fixtures, and statistical tolerance analysis can replicate the functionality of the physical nominal buck, while offering significant advantages. These include reduced lead times, lower material consumption, enhanced data traceability, and increased process flexibility. Furthermore, the ability to simulate and analyze variation digitally supports more robust design decisions and facilitates global collaboration.

However, the study also identifies several challenges. These include software limitations, the complexity of implementation, and the need for new competencies and workflows in Polestar's organizational structure. A successful transition to virtual verification therefore requires not only technical adjustments but also organizational and cultural shifts.

In conclusion, the integration of virtual geometry assurance tools and replacement of the current physical nominal buck is possible. Furthermore, it presents a viable path forward for Polestar to enhance its verification processes. While a complete replacement of the physical nominal buck may not be immediately feasible, a hybrid approach, where virtual tools complement physical methods, offers a realistic and impactful intermediate step. The findings support Polestar's broader sustainability and innovation goals and contribute to the ongoing evolution of digital manufacturing in the automotive industry.

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A

Interview Questions - PE Geometry

Questions posed to employees at PE Geometry as part of the qualitative study:

Geometry Assurance Engineer & 3D Scanning Personnel

1. Is it okay that we record this meeting and use it in our thesis in accordance to GDPR?
2. What is your position and what are your primary work tasks?
3. What kind of CMM methods have you used for digital geometry modeling?
4. Which CMM techniques do you find the most valuable?
5. What kind of 3D scanning hardware does PE Geometry use?
6. What kind of parts have the 3D scanner been used for thus far?
7. Have you used the 3D scanning to accomplish any significant results for partner companies in regards to geometry assurance?
8. What advantages/disadvantages do you see with using 3D scanning of components within the virtual geometry assurance verification process?
9. What are the main problems you have encountered when 3D scanning?
10. Do you think the 3D scanning process could be automated and suitable for scanning a variety of parts of different geometries and sizes?
11. To what extent have you performed virtual fixturing?
12. What are the advantages/disadvantages with virtual fixtures?
13. Do you think it would be viable to use scanning methods to verify geometry assurance during large scale production?

Geometry Assurance Expert & Polestar Consultant

1. Is it okay that we record this meeting and use it in our thesis in accordance to GDPR?
2. What is your position and what are your primary work tasks?
3. How does communication work between the department in China and department in Sweden?
4. How does communication work between the department in England and department in Sweden?
5. When other departments create specifications of measurements and send to you, have they done these measurements physically or digitally?
6. Is it easy or difficult to transfer information regarding design changes?

A. Interview Questions - PE Geometry

7. What advantages and disadvantages do you feel comes with this type of communication?
8. Does the time-zone difference pose challenges in working methods?
9. How many softwares do you use for daily work?
10. How many types of files do you handle on a daily basis?
11. Is the conversion between file types difficult?
12. Describe the step-by-step communication process needed in daily work operations.

B

Interview Questions - Polestar

Questions posed to employees at Polestar, in both Gothenburg, Sweden, and Chongqing, China, as part of the qualitative study:

Team Leader & Audit at the Plant, in Chongqing

1. Is it okay that we record this meeting and use it in our thesis in accordance to GDPR?
2. What is your position and what are your primary work tasks?
3. How many people are working on the nominal buck at the plant in China?
4. How many people are physically measuring components for the nominal buck?
5. Is it a physically exhausting or difficult process?
6. How many different types of components are there in total?
7. How often are parts not within tolerances, and therefore geometrically unacceptable?
8. How often do you have to implement design changes for the physical nominal buck?
9. How much time do the design changes take?
10. How do you store information about geometrical deviations, is all this data collected and stored somewhere?
11. Have you worked with virtual geometry assurance before you started working at Polestar?
12. Are you working with RD&T at the plant in China?
13. Do you think it would be beneficial in terms of costs, sustainability, and efficiency to have a digital/virtual nominal buck verification process?
14. Do you think it is possible to implement a virtual nominal buck verification process?

Planner & Leader for Nominal Buck Activities, in Chongqing

1. Is it okay that we record this meeting and use it in our thesis in accordance to GDPR?
2. What is your position and what are your primary work tasks?
3. Can you explain what a nominal buck is?
4. What does the current nominal buck verification process look like step-by-step?
5. What kind of tools do you use for measuring geometrical deviations?
6. How do you verify material quality?
7. How many products from each batch are tested?
8. Do you assume that all parts are okay if all parts from the sample are okay?

9. How do you decide if parts are okay in relation to each other?
10. How long does it take to perform a nominal buck verification from first design to ready-to-manufacture model?
11. How many different types of parts are tested in nominal buck?
12. Do you think it would be beneficial in terms of costs, sustainability, and efficiency, to do the verification process digitally instead?

Specifier of Manufacturing Requirements for Nominal Buck & Supplier Contact Person, in Chongqing

1. Is it okay that we record this meeting and use it in our thesis in accordance to GDPR?
2. What is your position and what are your primary work tasks?
3. What is the total cost of investing in a nominal buck?
4. How many different suppliers are there?
5. What happens with parts when they are not within geometrical tolerances step-by-step?
6. Has it happened that you must change suppliers, because of problems with supplied components?
7. How has it affected the process?
8. How long does it take from placing the order of nominal buck to delivery?
9. Has it happened that delivery of nominal buck is later than expected?
10. Has there been problems with nominal buck delivery in the past?
11. Do you think it would be beneficial for Polestar to perform the nominal buck verification process digitally instead?

C

Interview Questions - Outside Organizations

Questions posed to employees from outside organizations as part of the qualitative study:

Senior Analysis Engineer, Volvo Cars in Gothenburg

1. Is it okay that we record this meeting and use it in our thesis in accordance to GDPR?
2. What is your role and work tasks at Volvo Cars?
3. Are you working with geometry assurance and if so, how?
4. What steps have Volvo Cars taken to improve their digital geometry assurance process?
5. What kind of technology does Volvo Cars use for geometry assurance?
6. Does Volvo Cars currently use the RD&T software in digital geometry assurance? If not, what kind of software do you use?
7. Does Volvo Cars use virtual fixturing in the digital geometry assurance process?
8. Does Volvo Cars use virtual matching in the digital geometry assurance process?
9. How has the geometry assurance process been positively impacted by these changes?
10. Can you explain the digital verification process step-by-step?
11. What were the biggest challenges with implementing these changes?
12. Does simulations of geometry assurance pose challenges with large volumes of data handling?
13. Is it problematic to scan parts with a lot of holes or unusual geometries? If so, how do you scan these in an efficient manner?
14. What are the usual problems with using digital geometry assurance on a daily basis?
15. What are the advantages/drawbacks of using digital geometry assurance?

Kristina Wärmefjord, Deputy Head of Department & Professor. Lars Lindkvist, Docent. Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg.

1. Is it okay that we record this meeting and use it in our thesis in accordance to GDPR?

C. Interview Questions - Outside Organizations

2. What are your previous experiences regarding virtual geometry assurance?
3. Have you been part of virtual geometry assurance projects within automotive manufacturing?
4. Were these projects successful?
5. What steps did you take to achieve the result?
6. What kind of scanning method do you think is the most advantageous for automotive parts when talking about variation analysis?
7. Do you think CMM-probing is necessary to achieve a satisfactory result or is scanning enough?
8. Are scanned parts essential to achieve a realistic result when performing variation analysis of non-rigid components?
9. What do you think are the benefits of digital geometry assurance?
10. What are the limitations of RD&T in terms of performing realistic simulations?
11. Can RD&T handle a variation simulation of a fully scanned car assembly?
12. What information are companies missing out on when not using the free-state shape of a part when performing non-rigid variation analysis?
13. Do you think a complete automation of the geometry assurance process is possible?
14. How do you see the future of geometry assurance employing virtual tools like RD&T?

D

Quantitative Form Questions

The questions in the question form part of the quantitative study that is sent out to people with expertise in the field:

General

1. Are we allowed to store and use your answers for this master thesis project in accordance to GDPR? Your answers are anonymous.
2. Within which sector do your company operate?
3. Are you familiar with digital/virtual tools for geometry verification processes?
4. Is your company's current geometry assurance verification process performed physically or digitally?
5. Do you use any specific software for simulations or calculations of geometry verification processes? (If yes, please specify which software).
6. Select a number which best describes how effective your current geometry verification process is: 1 – 10

Digitalization

7. Is your company actively work towards digitalizing the geometry assurance verification process?
8. If you are currently measuring and verifying products physically, do you think digital tools would be beneficial?
9. If your process is primarily physical, how do you think a digitalization would be beneficial to you?
10. What do you think is the greatest barrier to digitalizing your company's geometry assurance process?
11. On a scale from 1 to 10, how willing would you be to digitalize your company's geometry assurance process?

Sustainability & Workplace Impact

12. Do you think your physical verification process is ergonomically straining/stressful for workers? (If you are digitally verifying, skip this question)
13. Do you believe a digital geometry assurance process would be more sustainable in terms of: (Select all that apply)
14. Do you think a digital verification process would reduce material waste (compared to a physical method)?

Final Thoughts / Additional Feedback

D. Quantitative Form Questions

15. Do you have any other comments or insights regarding the digitalization of the geometry assurance processes?

E

Scanning Procedure and PolyWorks

This appendix will serve as an explanation of how to proceed with the scanning procedure, as well as important steps in the PolyWorks software. First, there is an introduction to the necessary tools, equipment, and software necessary to obtain the scan data. Once a layout has been collected from the virtual fixture module described in Chapter 4.13a the actual scanning can be performed. This was done at the PE Geometry office in Mölndal. To be able to complete this step, the following tools and equipment are needed:

- Measurement table
- Three portable fixtures with spheres on top
- Scanning equipment
- Computer with PolyWorks

The equipment and tools belong to PE Geometry. The measurement table and portable fixtures have been manufactured by TMP Tooling. Each fixture has three legs with a sphere on top. The fixtures can be mounted on top of the measurement table by screws inserted into holes into the table surface. By having three legs, each one is adjustable in both height and slope in every direction, which allows the user to change the sphere location according to exact coordinates. It is of major importance that the fixtures are rigid and stable once every screw has been tightened. Any type of shift in the sphere placement during the scanning process will affect the scan data negatively. Likewise, it is of importance that the measurement table is perpendicular to the gravity direction. However, as the table is also scanned (which will be explained more in depth later), PolyWorks will be able to recognize the surface plane of the measurement table. The measurement table from TMP Tooling can be seen in Figure E.1.



Figure E.1: The measurement table from TMP Tooling used during the case study.

For scanning equipment, an MCAx S 7-axis articulated portable CMM arm geared with a ModelMaker H120 laser scanner, supplied by Nikon Metrology, was used (see Figure E.2). The articulated arm is assembled to the measurement table, but can easily be moved around to other places of the table if needed. The scanning equipment in turn is directly connected to a computer with tables that allow the scan data to be transferred immediately to whatever software is used to process the scan data. In this case PolyWorks is used, and RD&T is also adapted to the import of PolyWorks files at later stages. In the next section, a step-by-step guide of the scanning procedure as well as the necessary work conducted in PolyWorks is described.



Figure E.2: The articulated CMM arm and laser scanner from Nikon Metrology used during the scanning process.

E.1 Step 1: Scanning Preparation - Setting Up the Sphere Fixtures

The first step involves setting up the sphere fixtures and choosing the right locations based on coordinates from the sphere alignment layout presented in Section 4.3.2.3. The necessary equipment for doing this, apart from the previously mentioned scanning tools and fixtures, involves:

- Folding rule or tape measure
- Spirit level

As can be seen from Figure E.3 each sphere has a x-, y-, and z-coordinate. The three points will form a reference system with planes based on the angles between the spheres in the RD&T model. As can be seen, sphere 1 has coordinates (0,0,0) and is therefore in the centre of the coordinate system.

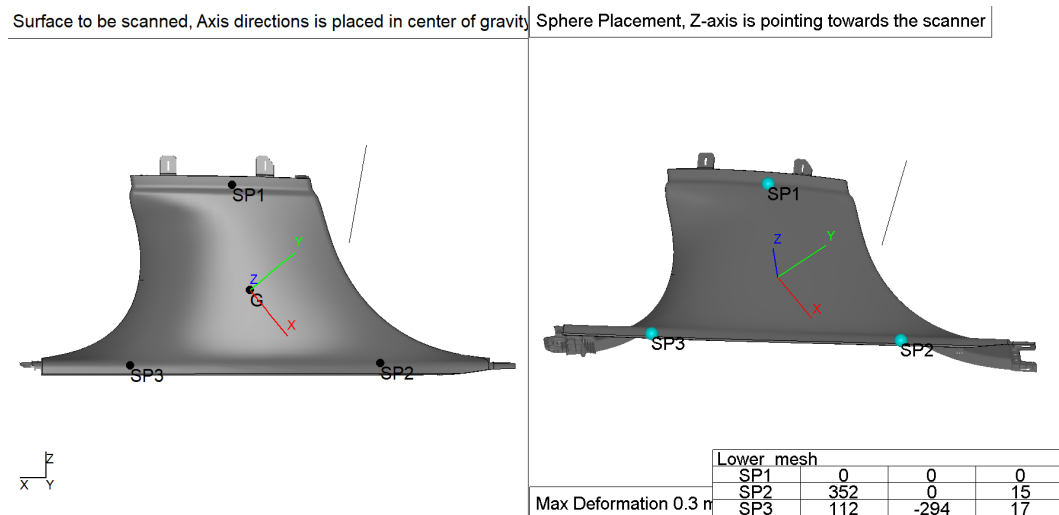


Figure E.3: The sphere alignment layout.

It is easiest to build the fixture for sphere 1 first and proceed from this fixture. It is also preferably to start by calculating the distances between each point in the system using only the x- and y-coordinates with simple euclidean geometry, and comparing their z-coordinate and altering the height accordingly as a final step. The 2D distance is calculated by taking:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (\text{E.1})$$

This is done between every two points so all three distances in the sphere triangle are calculated. For example in this case, the distances are the following:

- SP1 - SP2: 352mm
- SP1 - SP3: 314.6mm
- SP2 - SP3: 379.5mm

The fixture for sphere 1 is placed first. As can be seen, sphere 1 has the smallest z-value so it should preferably be placed quite low as the other fixtures will have their legs extended so they have higher height. Once the first fixture is placed and locked with all screws, a folding rule or tape measure, or any other kind of measuring equipment, is used to obtain an approximate location of the two other fixtures. It does not need to be exact on the millimetre, as the exact sphere locations can also be loaded into the RD&T software at a later stage. Once the initial positioning is done and the legs of every fixture are fixated to the table, the exact location can be set by tilting the legs. Once all fixtures have the correct positions, which can be ensured by measuring the distance between every two spheres, the final step is to change the height. This is preferably done by using a spirit level. The spirit level can be placed right under one of the spheres, then point the level to the direction of another sphere. The spirit level can be used to used as a guideline to make sure that the height of the next sphere is measured perpendicular to the gravity direction. A folding rule or tape measure can then be used to measure the distance from the bottom of the spirit level up to the bottom of the sphere. In this way the height

can easily be measured and altered according to the layout specifications.

Once all fixtures are in place, and all spheres have the correct distances and heights to each other, it is important to make sure that all screws are completely tightened so each fixture is rigid. For example, Figure E.4 shows the finalized setup of the fixtures according to the layout in Figure E.3.



Figure E.4: The finalized sphere setup for the lower part used in the case study.

E.2 Step 2: Scanning Procedure - Open PolyWorks and Gather Scan Data

Once the fixtures are in place the next step is to open up PolyWorks and begin the scanning procedure. The important thing is to be aware of that there should be two different scan objects, one for the spheres and measurement table, and one for the part itself. This is necessary as the scan data of these two will be exported

separately and used for two different purposes at a later stage in RD&T.

The user can locate the tools for the scanning process under the **Device** menu (see Figure E.5). As can be noticed, the software correctly shows that a Nikon Metrology Scanner is connected to the computer. One can then make sure the scanner is activated and then click on **New Scan** to start the scanning process.

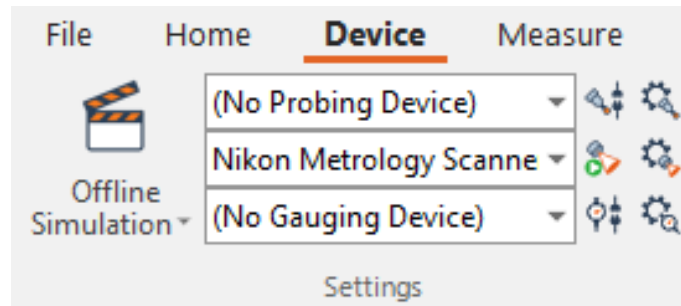


Figure E.5: An overview of the available scanner device as well as the option to start scanning.

a) Scan the spheres and table

After this another window comes up which allows the user to change preferences according to the scanning process. During this step, either the measurement table and spheres can be scanned first, or the part, the order does not affect the results. In this case the table and spheres were scanned first. If the objective is to scan the table and spheres the final data type can be of either polygonal model or point cloud from mesh. It is also sufficient to do only a **surface scan** for this scan type.

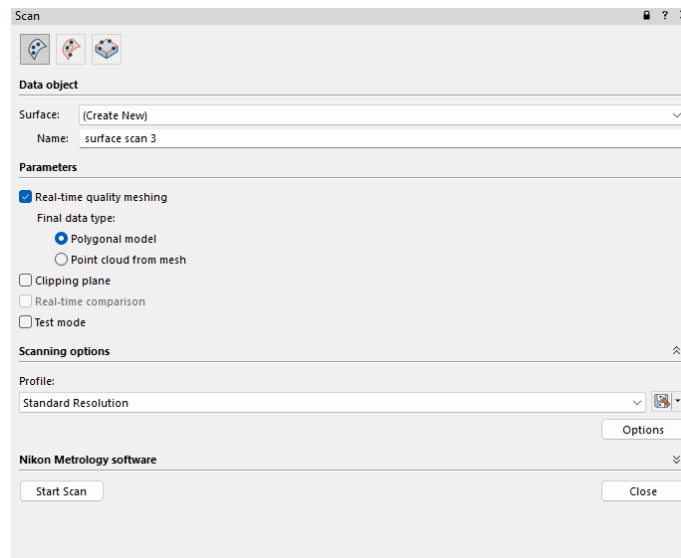


Figure E.6: The scan specification window.

Once the button **Start Scan** is clicked the scanning process can begin. Scan the

table (at least a part of it) and the spheres. It is not necessary to scan the legs of the fixtures, but it is important that the spheres are scanned so it is noticeable that it is a sphere. The table and spheres will later have features created in these objects so the software need to recognize that it is a plane and spheres. Once these scans are completed, it should look something like Figure E.7. it may be noise or incorrect scan data in the view, such as if parts of the legs are picked up as data points during the scanning, but these can be removed afterwards during postprocessing.

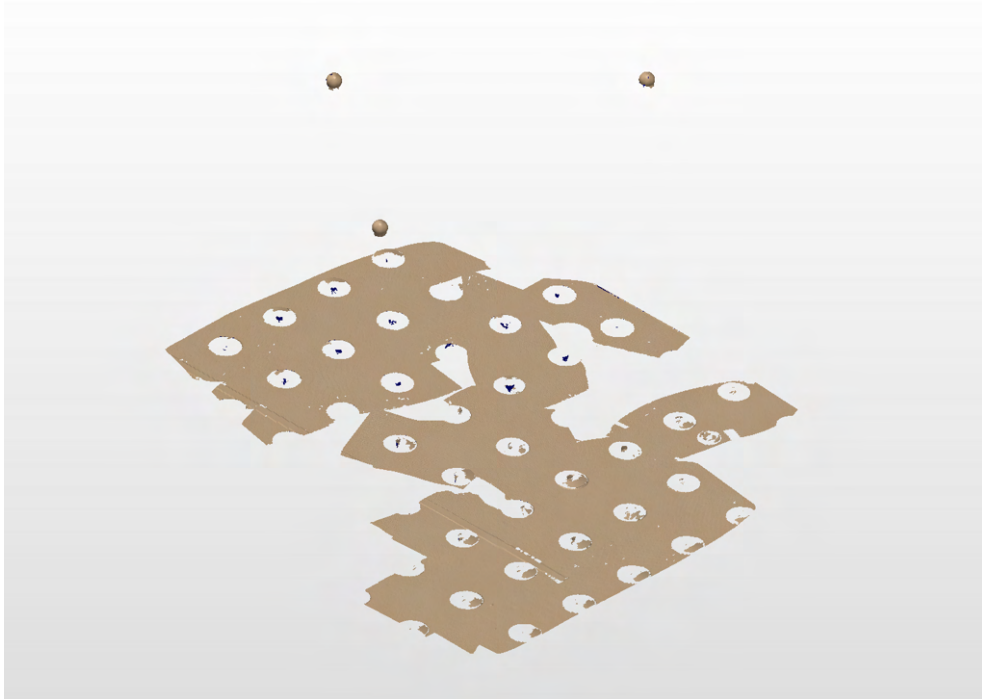


Figure E.7: The scan of the table and spheres .

b) Scan the part

Once the scanning results of the spheres and table are satisfactory, press **End Scan** and start a new one in the same window as Figure E.5 before. The next step is to scan the part. For this, the scan needs to be of type **surface + boundary scan**. This is very important, as the boundary scan will later be exported as a text file which tells in which coordinates the edges of the part are located. The final data type can be either polygonal model or point cloud from mesh. Once these settings are finalized, place the part on the spheres and click **Start Scan** in the PolyWorks software. Then proceed with scanning the part. Make sure to do a careful scan of the surface, including edges and holes, to make sure the scan data gives an accurate representation of the physical part. See Figure E.8 for how the scanning process looked during the case study. The visual representation of the scan data can immediately be seen in the PolyWorks software, allowing the user to recognize if the scan results are correct.



Figure E.8: The scanning process during the case study. Note that in this case it is part Intermediate, which is the other part used during the case study. The text and other figures refers to the other part Lower.

Only the top surface should be scanned as have been mentioned before. In some cases an error message might pop up that there is an misalignment in the scan data. This problem may arise if the part is moved during the scanning process, which is why it is of importance that the fixtures are entirely rigid and that the part is stable on the spheres. It can also be because the scan was not done carefully enough, in which it is sufficient to only dismiss the error message and redo the scan. Once the full scan is done and the button **End Scan** is clicked and the scan data is processed (by removing noise and making the scan data clean), it should look something like Figure E.9. Note that the green edges are clearly marked which is the edge scan.

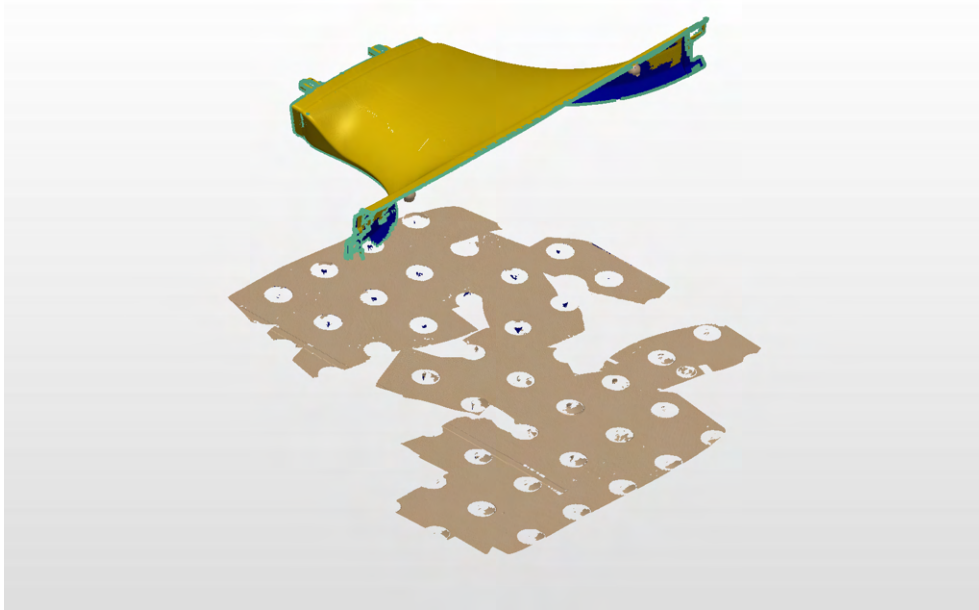


Figure E.9: The scan of the part.

c) Clean up the scan data to make it similar to the CAD

It is very common that the scan data is not perfect once the scanning is done. It is easy for the scanner to pick up data from the fixtures, or objects from the underlying part side, etc. Therefore the scan data needs to be cleaned up. This can easily be done by the available tools in PolyWorks, by simply zooming in on certain areas, marking data points, and deleting them. In Figure E.9 and E.7 the incorrect scan data has already been removed.

E.3 Step 3: Postprocessing - Import CAD Part and Create Features

Once the scanning is finalized the next step is to import a CAD file of the part and create features. There are three reasons for the importance of features:

1. Features of the spheres and gravity plane (measurement table) so they can be imported to RD&T.
2. Features that will be used to match the scan data to the nominal CAD so the scan data get the correct position and orientation in space. One will notice after importing the CAD that they will not have the same position automatically.
3. Features that will be used as measurement points to calculate the geometric variation in the scan data from the nominal CAD.

a) Import CAD

As a first step of the postprocessing, the user can start by importing a nominal CAD

to the software. This CAD will be used as a reference for the scan data cloud which will give the scan data the correct orientation in space. This will make it easier to match the scan data to the nominal mesh in RD&T at a later stage. Therefore, it is also important that it is the same CAD file that was used in previous steps in RD&T in order for the positions to match. CAD data is imported by clicking on **Import** in the home window, then **CAD Models...**, which will allow the user to select a CAD file of preference (see Figure E.10). In this case, a stp-file is used.

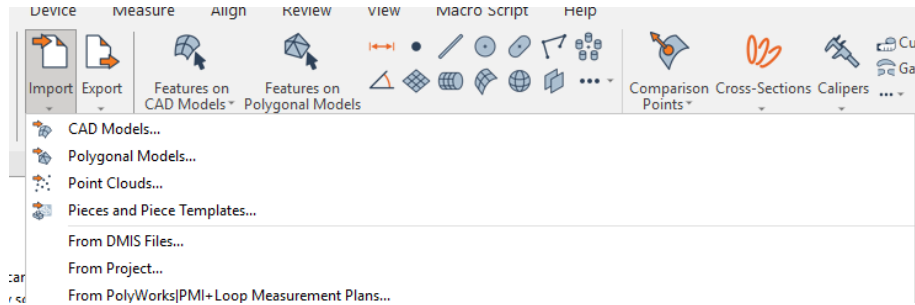


Figure E.10: The button for importing CAD data.

Once the CAD file has been imported, one can notice that the scan data and nominal CAD has different orientations and positions in space (see Figure E.11). To solve this issue, it is necessary to make use of features which is explained in the coming steps.



Figure E.11: The scan data and reference CAD data. The scan data must be moved to the location of the CAD for further analysis.

b) Create features - Spheres and gravity plane

The next step is to create features on the nominal CAD. These features are geometrical objects such as planes, holes, and slots that exist on the scan data or CAD. The first objective is to create features on the spheres and measurement table, so these define the three spheres and gravity plane. First it is preferable to hide the part scan and CAD from the view by hovering over them in the object tree and clicking the scroll button on the mouse, to be able to see the spheres and measurement table

much more easily.

Features can be added by clicking on **Features on CAD Models**, and then **Pick on CAD Models**, which allows the user to pick features from the CAD model (see Figure E.12). If holes, slots, planes, or other geometrical objects are clicked, the software will usually automatically detect the object and correctly create a feature in the correct spot.

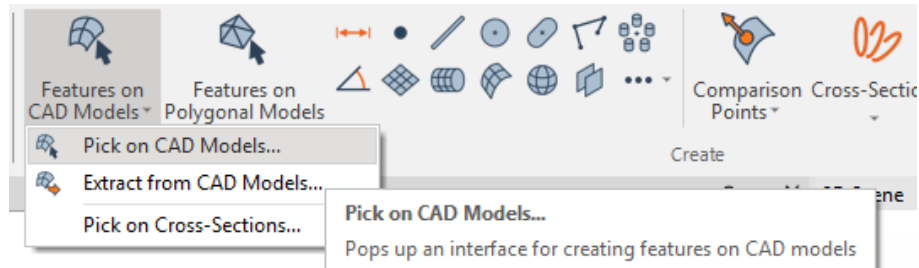


Figure E.12: The button for creating features, which will auto detect features once clicking on geometrical objects.

The next step is to proceed with creating a feature for these four objects - the three spheres that were scanned earlier as well as the measurement table. The software will detect the spheres as being spheres and the measurement table as a plane. Create a new feature for one and each of these objects. They must then be named specifically **sphere 1**, **sphere 2**, **sphere 3**, and **Gravityplane**. The numbering of the spheres must be consistent with the numbering of the spheres in the sphere layout in Figure E.3. Once these four features have been created, it should look like Figure E.13.

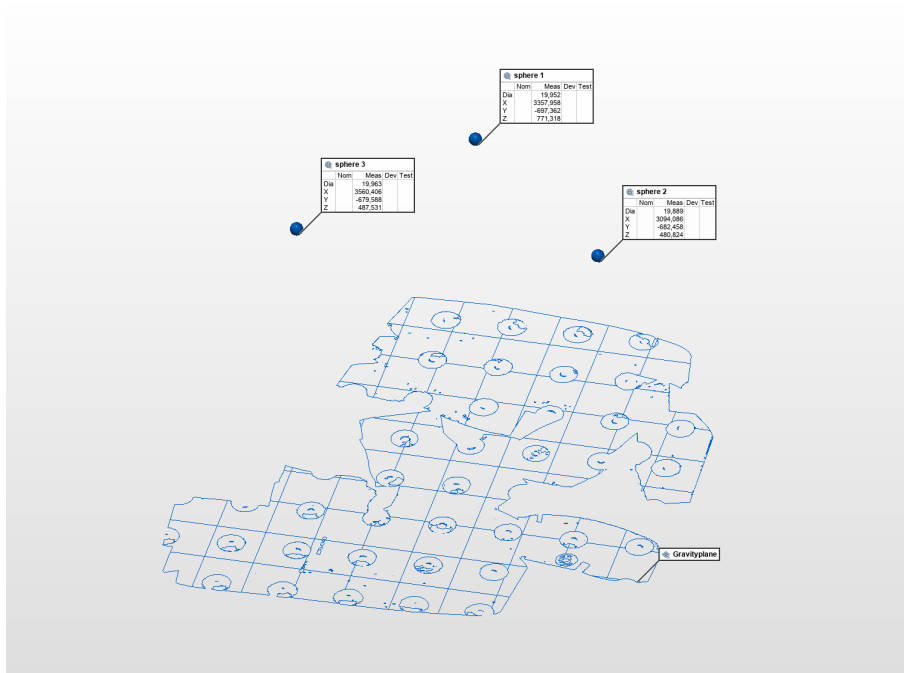


Figure E.13: The model window once features for the spheres and gravity plane have been created.

c) Features - Objects for matching scan and CAD

The next step is to create features that will be used to move the scan data to the same position and orientation as the CAD in space. These features should be picked on the surface of the scan. The software will then be able to match the location of the features on the scan contra the CAD make the movement. For the part used in the case study, five planes and one slot were used as objects to create a positioning system that was used to move the scan data. Figure E.14 shows for example how the feature for a slot located on scan surface was created. The method **Fit** and **Fit to Elements** was used, which allow the user to mark the area of the geometrical object so the software can create an automatic feature in that spot.

E. Scanning Procedure and PolyWorks



Figure E.14: The slot marked with the window open for doing a best fit to create the slot feature.

The feature do not need to be based on 3D PMI data as it is only used temporarily to move the scan. The features should be spread out on the scan surface so the part gets the correct orientation throughout the whole geometry. It is also a good idea to give each feature used in the positioning system a specific name pointing to that use, which is shown, for example, in Figure E.15. Furthermore, to continue with the next step of aligning the CAD and scan, the user can mark all these features and go to the **Align** window and then click on **Data to Reference Objects** to do a best fit which will move the scan to the position of the CAD.

E. Scanning Procedure and PolyWorks

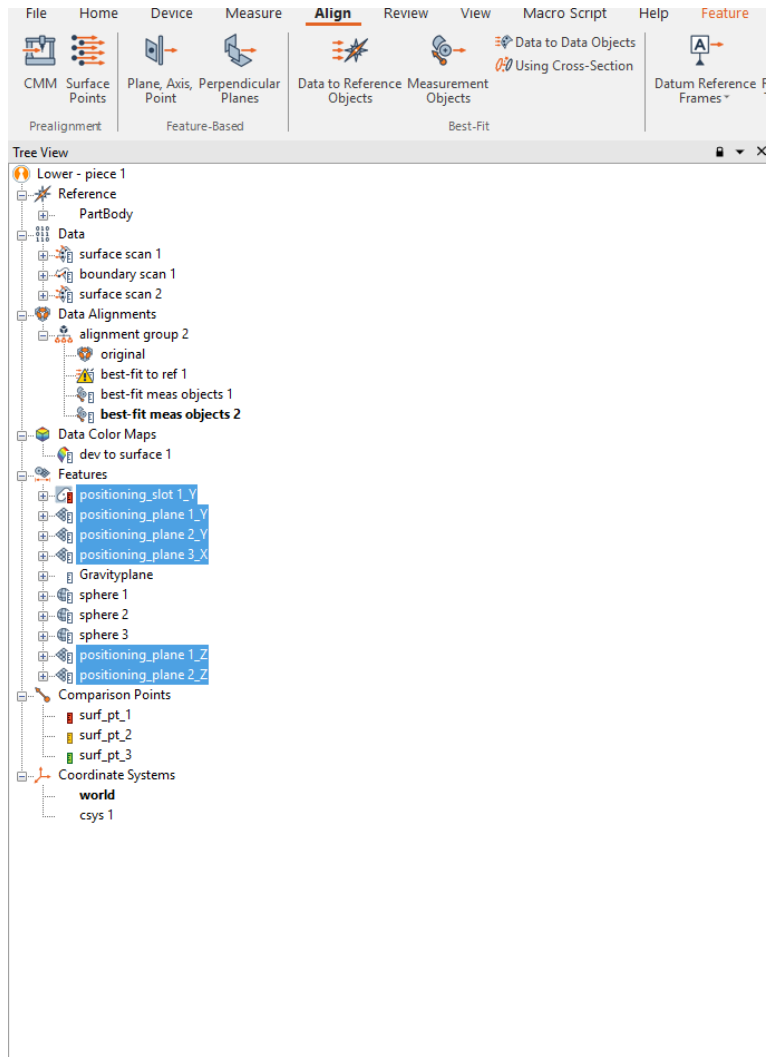


Figure E.15: The object tree with the features used to position the part marked.

Once clicked the user will be able to specify the best fit options (see Figure E.16). As can be seen it can be specified in which directions the features should lock the part according to its positioning system. As the 3D PMI data is not used, this is specified by the user, but should be logical in terms of how the part is intended to be positioned. The scan data of both the table and spheres as well as the part should be used in the alignment. The alignment should then be automatic and the scan data will be moved to the reference (CAD) location. In some cases the best fit might not work. In that case the user can click on target points in the CAD and match each target to the features created in the scan, which then will make the scan change its position and orientation.

E. Scanning Procedure and PolyWorks

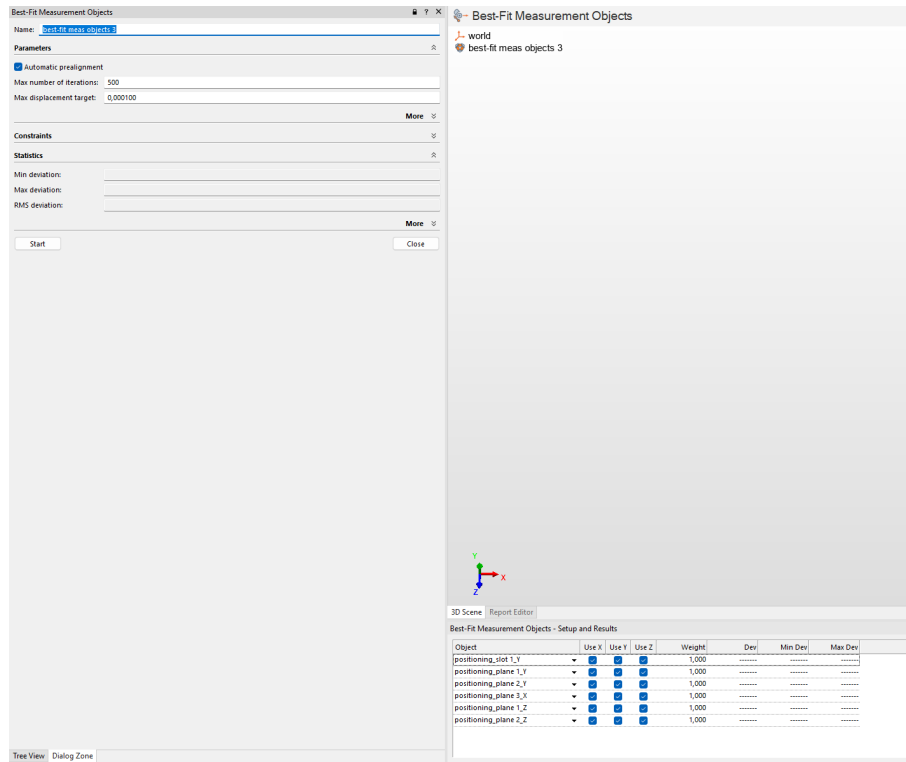


Figure E.16: The best fit alignment window.

Once completed, the scan will change orientation and position (see Figure E.17). One can notice immediately that there is geometric variation in the scan data compared to the nominal CAD.

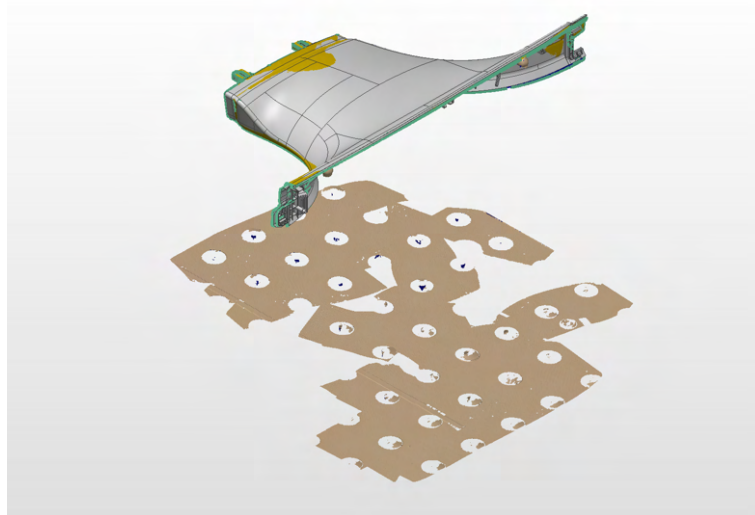


Figure E.17: The scan data after the best fit is completed and the scan data has been moved to the position of the CAD.

d) Features - Objects for extracting values of geometric difference between scan and CAD

E. Scanning Procedure and PolyWorks

The final step is to extract measured values from features so the software analyzes the geometric variation between scan and CAD in these data points. In optimal cases, there are noticeable slots, holes, and other geometric objects located on the part surface, such as demonstrated in the example in Figure E.18. The example Figure has been taken from PE Geometry's internal virtual fixture course.

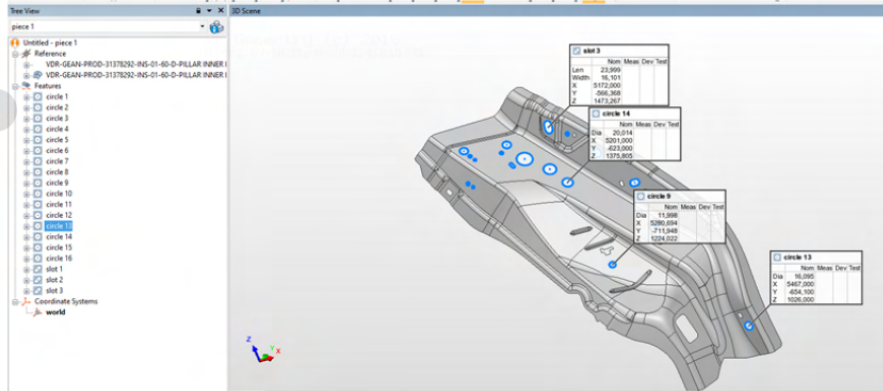


Figure E.18: An example part containing many geometric objects which are used to create features (PE Geometry, 2025).

The user can then right-click on the feature in the object tree and select **Extract Measured**. The software will then calculate the difference between nominal data and scan data values (see Figure E.19). Also this example Figure has been taken from PE Geometry's internal virtual fixture course.

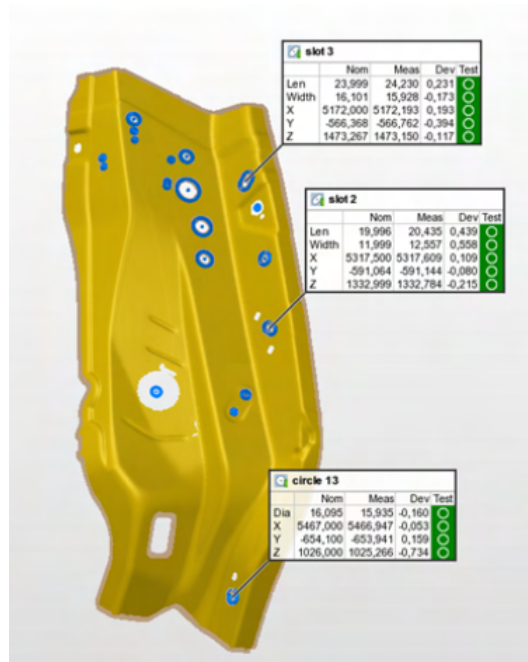


Figure E.19: An example where the features have had their measured values extracted (PE Geometry, 2025).

Users can potentially face some problems when seeking to implement features on parts. This may be because there are no suitable geometrical objects on the scan surface that can be used as features for extracting measured values. This was a problem during the case study, and a solution to how it was solved is explained in subchapter E.3.1. If there are no problems with creating features for extracting values, the next step is to export all important files which is explained in chapter E.4.

E.3.1 If there are no suitable objects located on the scan surface to use as features

The two parts that were used during the case study did not have suitable features on its surface to use as measurements between CAD and scan. It also seemed problematic if the feature measurement points were located in a surface which did not have a corresponding mesh node. The project group therefore had to come up with an alternative solution to solve this problem which included creating three surface points on the part in RD&T, with the same coordinates and normal directions of these points being used for the surface points in PolyWorks. This process will be explained below. Note that this is a specific case if the initial plan of creating features is not working.

a) Create additional points on a new part containing a mesh in the file from chapter 4.3.2.2 in RD&T

The first step is to create features as surface points on the part created in chapter 4.3.2.2 in RD&T. To be able to complete this step, three files are needed:

- The RD&T file from chapter 4.3.2.2 (**rdt-file**)
- CAD data of part (**jt-file**)
- A midsurface mesh of the nominal CAD of the part (**either a fem-, inp-, dat-, bdf-, nas-, blk-, ecd-, or k-file**)

Once the initial points (Y1, Y2, Y3, Y7, Z4, Z5, X6 in this case) from the 3D PMI data have been created for the part in RD&T, three extra points need to be created. These points will be the surface points that will be created in the PolyWorks file as features. They need to have the exact names (surf_pt_1, surf_pt_2, surf_pt_3) in RD&T as they are named such in PolyWorks, and it is important they have the same names from the BB calculations to work properly. These points will also be used in a new positioning system that will be used solely for the purpose of getting the scan data correctly imported to RD&T.

These three points will be picked from the surface of the part. As can be seen in the list of necessary files mentioned above, one necessary file is a midsurface mesh of the part. The reason is found in this step. Each one of the three surface points must be located in a node in the mesh. This is because the software will not be able to locate the correct points when matching the scan data to the mesh if this is not the case. However as it is a midsurface mesh, the mesh has no thickness. Therefore, one issue is that picking a point from a node of the mesh will lead to the point being located inside the CAD part, which also is incorrect, as the point needs to be located in a node while simultaneously being located on the surface of the CAD part. This can be solved by following the steps below. Be aware that meshes need to be created using another software as it is currently not possible to create meshes in RD&T. A guide for creating midsurface meshes is explained in Appendix F.

First, a new part can be created which will contain the mesh. In this model the three points will be selected, each one from a node in the mesh. A mesh can also be imported to the existing part containing the jt-file. However, it is not possible to hide the jt-file while only making the mesh visible, thus making it difficult to locate a node in the mesh. By creating a new part for solely the mesh, the other part containing the jt-file can be hidden from the view, making it possible to select a point in a mesh node much more easily. This mesh model is therefore only needed temporarily. The first step is therefore to click on **Handle Parts** (see Figure E.20).

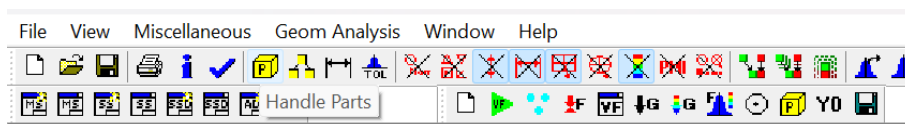


Figure E.20: The button for handling of parts.

Then click on **New** to create a new part. In this case the part is named **Lower-Mesh** to be able to easily recognize the part containing the mesh. Then click on the window called **Compliance**. This window allows the user to import meshes to

RD&T. Then click on the button **Load Mesh** (see Figure E.21).

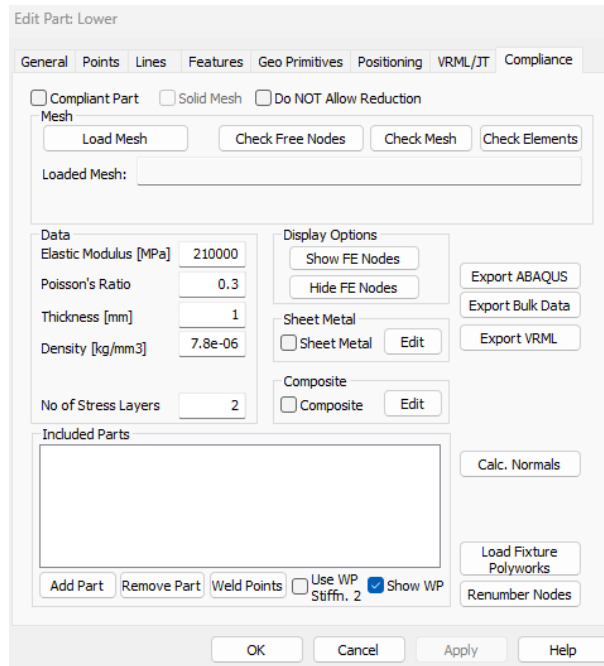


Figure E.21: The compliance window used to load meshes.

Another window then opens up which allow the user to select the mesh file. The initial choices are mesh files of either inp-, dat-, bdf-, nas-, blk-, ecd-, or k-type (see Figure E.22).

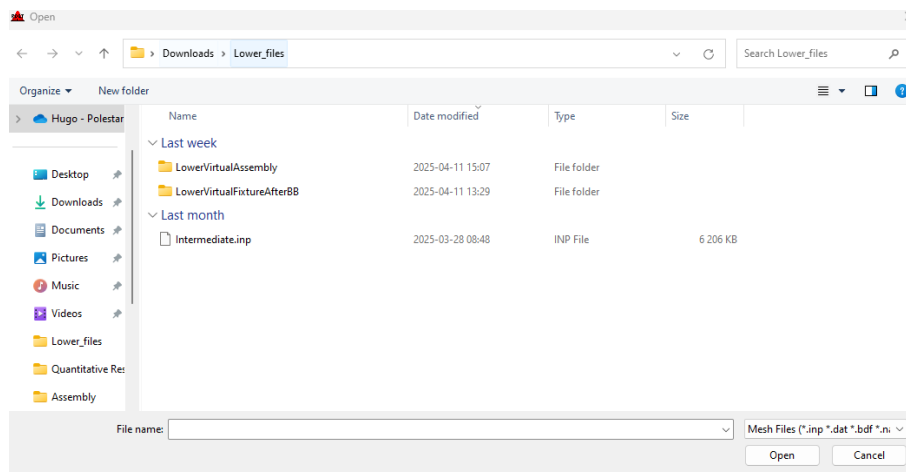


Figure E.22: The window which allow the user to import mesh files.

However one can also change to **All Files** and choose fem-files for example (see Figure E.23).

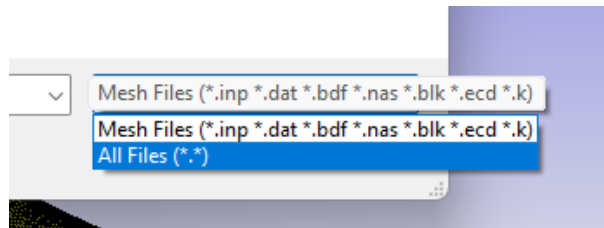


Figure E.23: Changing to All Files allow the user more file options.

In this case a mesh file of fem-type was loaded for the Lower part. One can also notice that the box **Compliant Part** is clicked once the mesh has successfully loaded into the software. Now close the window because no other options need to be changed in the part window.

Once the mesh is loaded into the software it can be viewed in the main window. First, the part containing the jt-file must be hidden. This is done by clicking on **Handle Parts**, then the part containing the jt-file (Lower), and click **Hide**. Then only the mesh will be visible, see Figure E.24 for how the mesh for part Lower looks in the software.

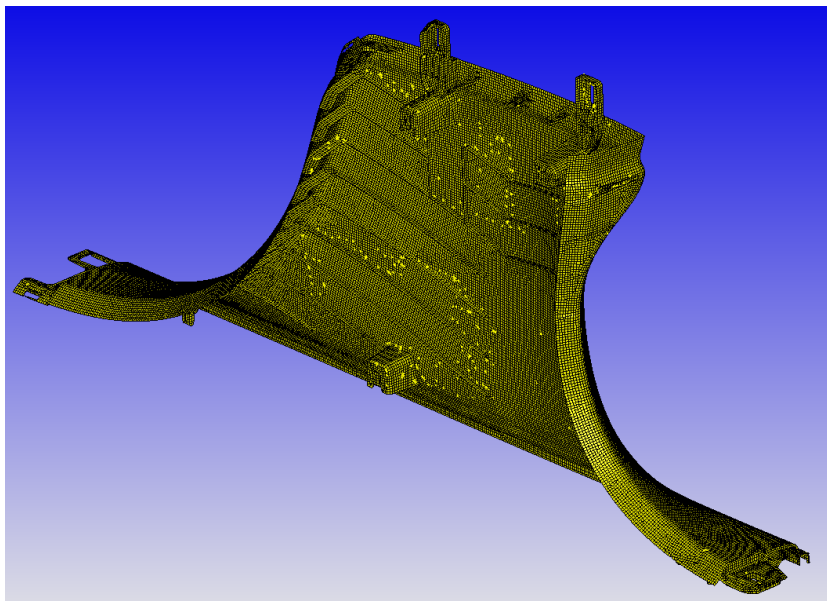


Figure E.24: How the mesh looks once implemented in RD&T.

The next step is to pick three points, each one from a node, on the top surface of the part (the surface that later will be scanned). Go to the **Handle Parts** interface once again, make sure to open up the part that contains the mesh by clicking on the name of the part then **Edit** and click on the **Points** window. As can be seen from the list, there are now many points imported for the part. Each such point describes the coordinates of a node in the mesh. Next click on **New** to create a new point for the part. A window pops up that lets the user decide the options for this newly created point, as described previously. Now click on **Pick** and click on one of the

nodes in the mesh. The only guideline here is that the point must be located on the surface that later will be scanned. Preferably it should also only have one direction in its normal direction. When a point has been selected, the normal direction for the surface of that location will automatically be filled in. If one of the x-, y-, or z-coordinates is close to ± 1 (it does not have to be exact) and the other two close to 0, it can be deemed to have only one direction. Repeat this process for two other points, and name each point surf_pt_1_mesh, surf_pt_2_mesh, etc. to keep track of that it is a mesh point. It is beneficial to spread out the points on the surface. For example, the points cover up one corner each in this demonstration (see Figure E.25).

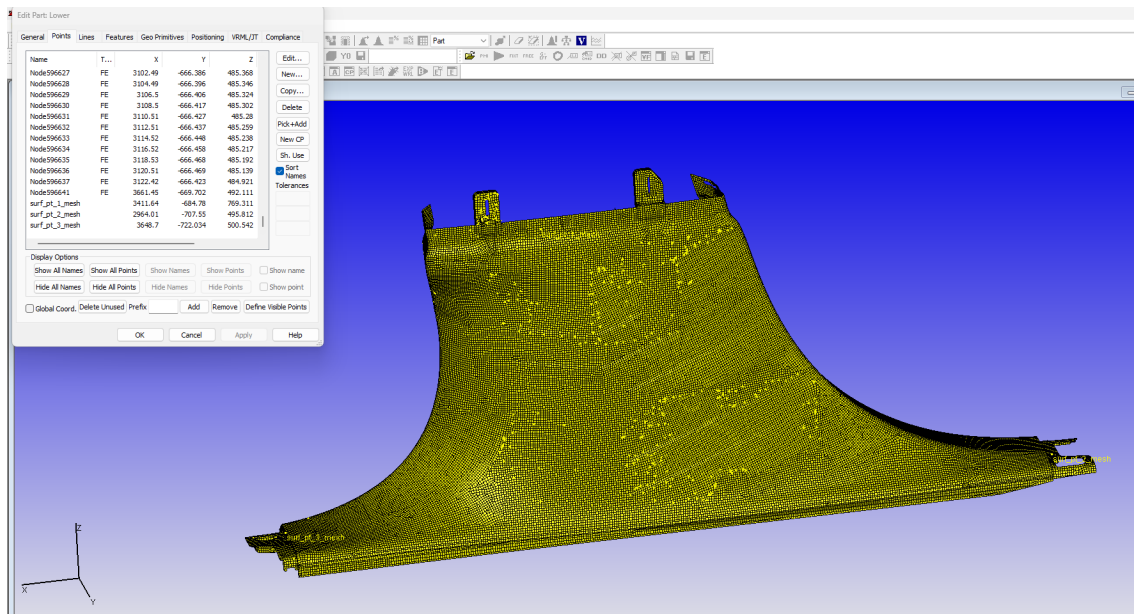


Figure E.25: The newly created points 1-3 implemented in the mesh model.

b) Create points on the surface of the part containing the jt-file corresponding to the normal direction of the mesh points created in the earlier step

Now the points are visible. The next step involves going back to the **Handle Parts** window, then open up the initial model only named **Lower** (and make it visible in the model window again). Now points need to be created on the surface of the part. The previous mesh points will be used as a guideline to make sure the new surface points are located in the normal direction of each point and therefore a mesh node, however they must be placed on the surface of the model containing the jt-file. Therefore click on **New** to create a new point, name it surf_pt_1, then **Pick on a Surface**. Now direct the view towards the mesh point surf_pt_1_mesh. Make sure you are faced directly toward the y-axis (the coordinate axis to the bottom left can help) as the mesh point has its normal direction toward the y-axis. Then click on the mesh point. A list will open to make sure that the user has selected the correct surface. Click **OK**. Now the new point should be located on the CAD surface while still being in the normal direction of a mesh node (see Figure E.26 that the mesh

point is located inside the part, while the other point is located on the part surface).

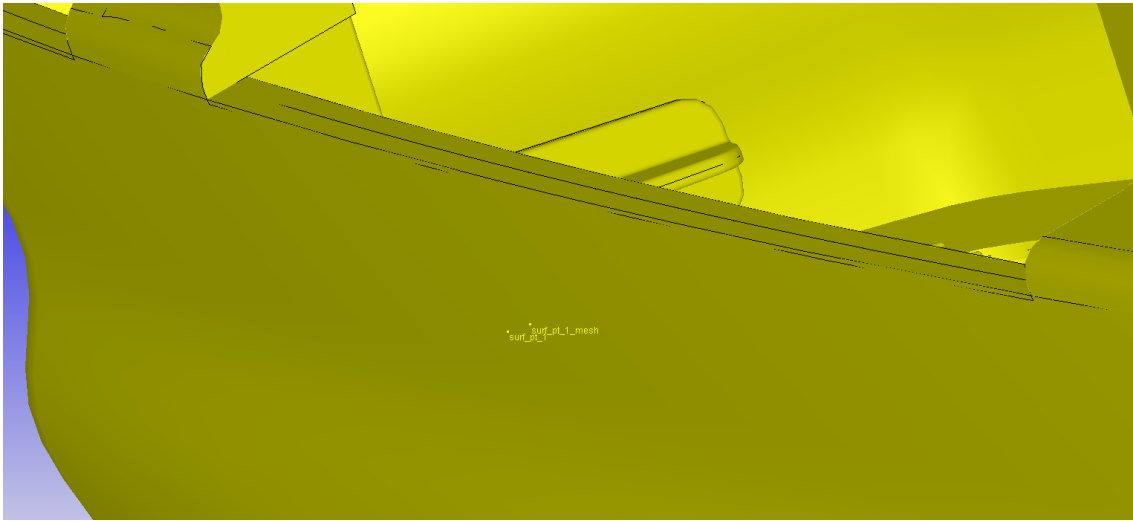


Figure E.26: The two points `surf_pt_1` and `surf_pt_1_mesh`, one located on the surface of the jt-file and the other on the surface of the midsurface mesh.

Repeat this for the two other points. By doing this, the user makes sure that the points are located on the CAD surface while still being in normal direction to a mesh node, which is necessary in order to adapt the scan data to the mesh model.

c) Create a new positioning system containing the surface points

It was also necessary to implement a new positioning system for the part Lower in order for the import of the scan data to work. Instead of using the initial positioning system containing solely points from 3D PMI data, an alternative positioning system was created. In this case, the 3D PMI data points Y1-Y3 were used for A1-A3, while `surf_pt_1` was used for B1, `surf_pt_2` for B2, and `surf_pt_3` for C1. Figure E.27 shows how this alternative positioning system looks before a target position was selected.

E. Scanning Procedure and PolyWorks

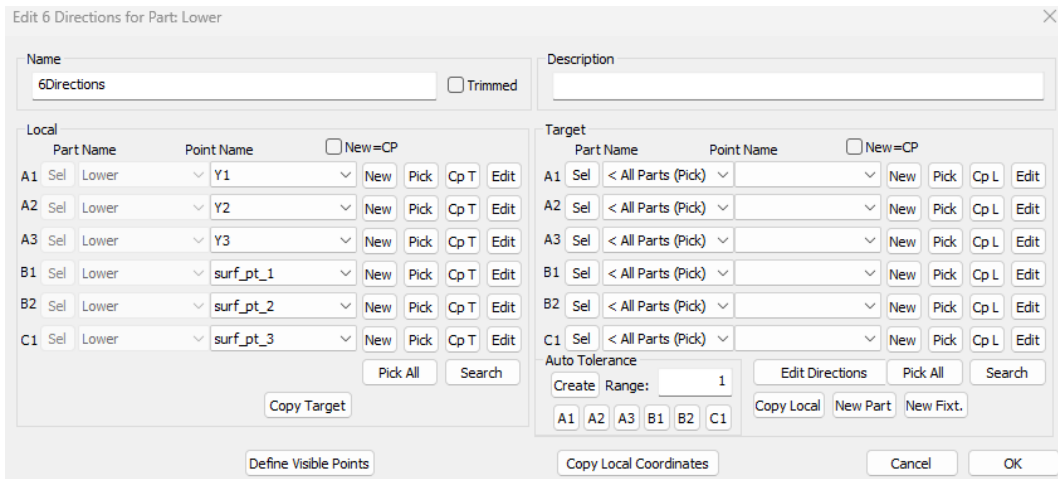


Figure E.27: All points when they have been selected in the lists.

The next step is to choosing Fixture01 as a target part. Then **Copy Local** to get the correct coordinates as target points.

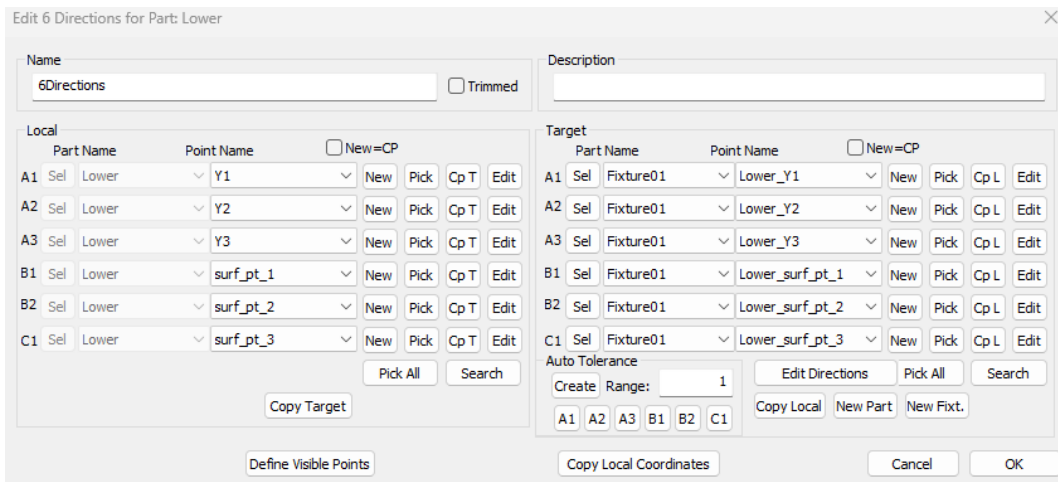


Figure E.28: The positioning system with both local and target points selected.

The directions also need to be correct. In this case, they should follow the intended directions of the 3D PMI data (even though the new surface points are not a part of it).

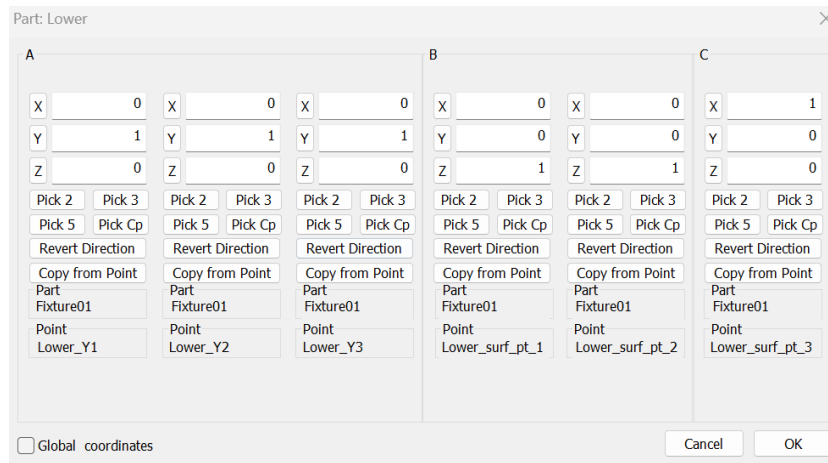


Figure E.29: The window for editing the direction of the positioning system.

Once the surface points and a new positioning system was created, this file was saved. This file was later used in the virtual fixture module explained in chapter 4.3.2.3 when the goal was to find the optimal sphere placement. The important thing for being able to get the correct surface point locations into PolyWorks is to write down the exact coordinates and normal directions of each point. Also save the file and make sure to use this file containing the correct positioning system when running the virtual fixture module.

d) Create corresponding surface points as features in PolyWorks

Once the surface points have been created in RD&T, the next step involves creating the same points in PolyWorks. In fact, RD&T is only used to make sure that the features are located in the correct locations (in a mesh node, on the part surface), as well as for altering the positioning system so RD&T can match these points. These points will be created using the surface comparison point tool. The first step is therefore to click on the **Comparison Points** tool and then **Surface** (see Figure E.30).

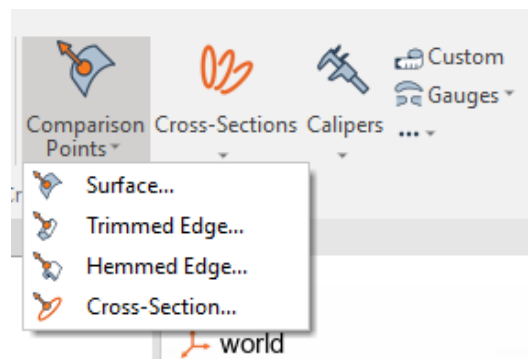


Figure E.30: The surface comparison point tool.

Once the tool has been selected the user can change parameters of the surface comparison point. The method should be **Numerically** as the coordinates and normal

directions will be specifically set and the same as the ones created in RD&T in the previous step. It is crucial that the points are the same in name as well as both position coordinates and surface normal directions. The parameters for surface point 2 can be seen below in Figure E.31. Note that the name is **surf pt 2**, which will be `surf_pt_2` in the later text files that contain the features, which is the same as the point in RD&T.

The screenshot shows the 'Create Surface Comparison Points' dialog box. The 'Name' field contains 'surf pt 2'. Under 'Creation method', the 'Method' is set to 'Numerically'. The 'Parameters' section is divided into 'Point' and 'Surface normal'. The 'Point' section has input fields for X (3411,657), Y (-684,450), and Z (771,471), with a 'Project' dropdown set to 'Z'. The 'Surface normal' section has input fields for I (0,005), J (-0,989), and K (0,148), with an 'Automatic' checkbox. Below these are 'Radius' (2,500), 'Link to object' (checked, set to 'Reference Object'), and 'Extract measured component' (checked). 'Create' and 'Close' buttons are at the bottom.

Figure E.31: Surface comparison point 2.

This is done for the two other surface points as well. Once all of them are created they should be visible on the CAD surface, and their measurement values can be extracted by right-clicking on each point and then **Extract Measured**. PolyWorks will then measure the difference between the CAD and scan data. Once this is done, all necessary features have been created. See Figure E.32 for an overview of the model once all features are created in the software, as well as a color scheme that shows geometric variation in the scan data.

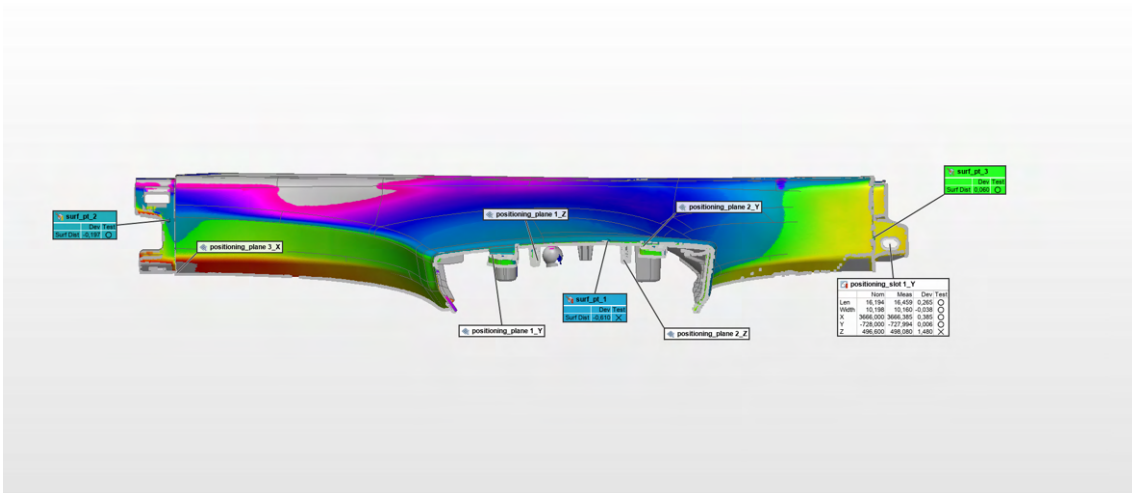


Figure E.32: All created features. Note that the surface points have extracted values.

E.4 Step 4: File Export - Export Necessary Files to RD&T

The last step before moving back to RD&T for further analysis is to export the necessary files from PolyWorks. Three files need to be exported which are the following:

- Surface scan data as an STL file which must be named NotAligned.stl. It contains the polygonal model of the scanned surface.
- Boundary scan data as an txt file which must be named Boundary.txt. It contains a point cloud of all the boundary points.
- All features as an DMO file which must be named Features.dmo. It contains all features with their nominal position and size and deviation based on the scanning. These features also include the spheres and gravity plane.

It is crucial that all the files have the exact names in order for the file transition to RD&T to work.

a) Export the scanned part surface as an STL file

There should be two surface scans available. Surface scan 2 contains the scan data of the actual part and is the correct file to export. Surface scan 1, on the other hand, includes the scan of the spheres and the measurement table, and does not need to be exported. These features are scanned solely to enable the creation of features, which are subsequently exported as described in Step c).

Please note: if the part was scanned before the spheres and table, it may be listed as Surface Scan 1 instead. In that case, select the appropriate scan.

Then in the **Data** window above, click **Export**, followed by **As Polygonal Model**

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(see Figure E.33). Save the file as an STL file with the name **NotAligned**.

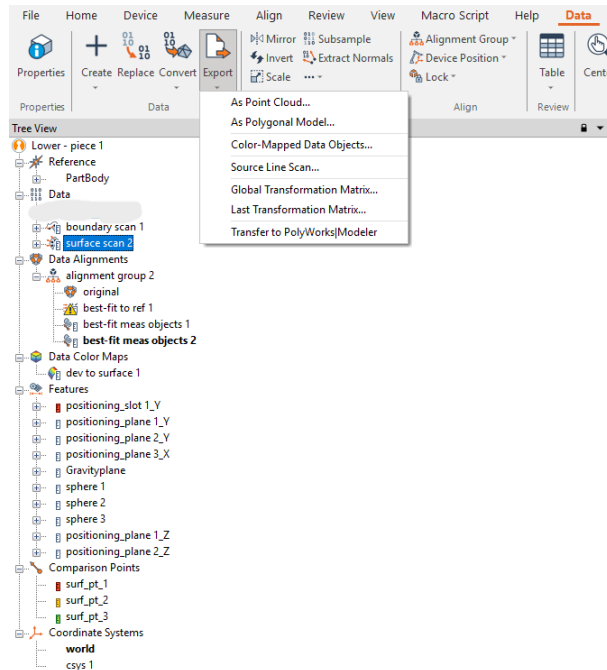


Figure E.33: Exporting the part scan.

b) Export the boundary scan as an txt file

Mark the boundary scan in the tree then click **Export** then **As Point Cloud**, then save it as an txt-file with the name **Boundary**.

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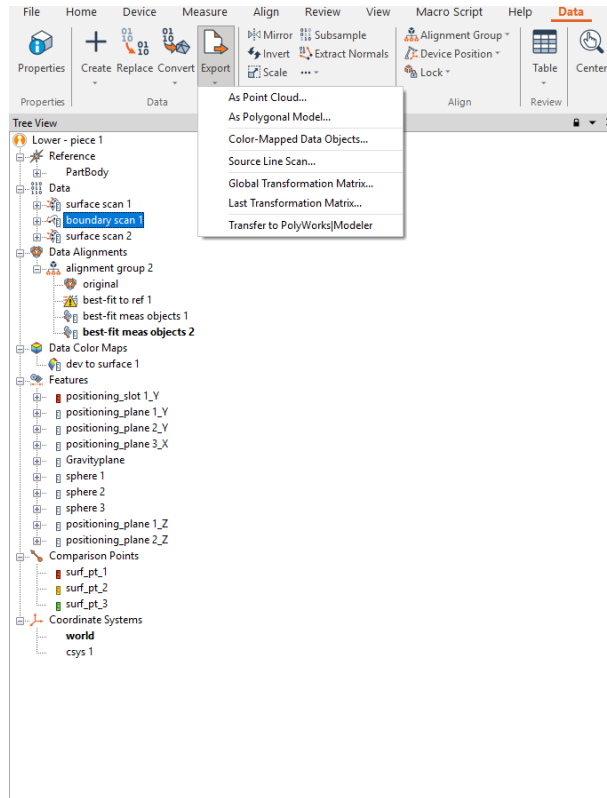


Figure E.34: Exporting the boundary scan.

c) Export the features as an DMO file

The final step is to extract some of the features as a DMO file. The correct features to export are the spheres, gravityplane, as well as the measurement points. The other features that were used to position the scan data and align it to the CAD should not be exported. Therefore mark the correct features, then enter the **Data** window, then **Export** and then **Features and Comparison Points as DMIS File**, and name it **Features**.

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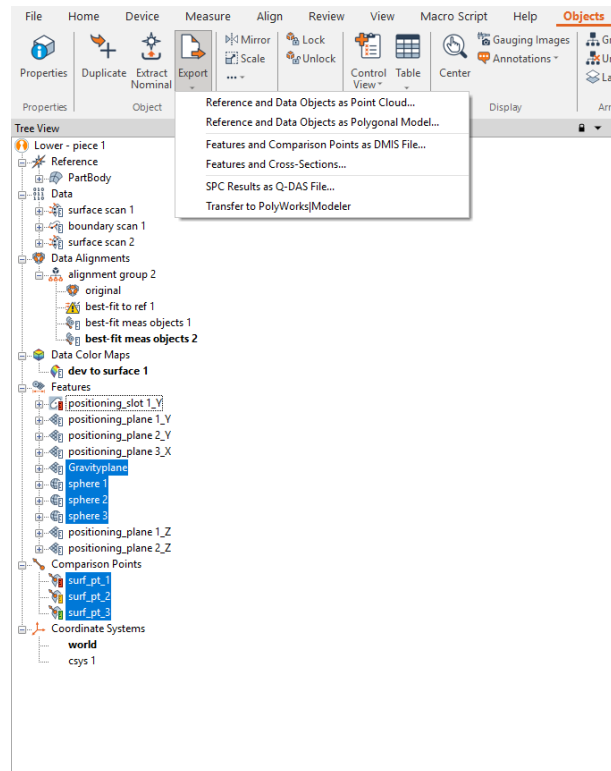


Figure E.35: Exporting the features.

Once this is done, all necessary files are obtained from PolyWorks and the scanning process is finished. The next steps continue in RD&T and are explained chapter 4.3.2.4.

F

Meshing Procedure

This appendix serves as an example and guide for meshing CAD models intended for use in simulation. The case presented is specifically from the thesis's case study. Only one component will be meshed and explained in detail, as the same procedure was applied to all models. The program used for meshing was the student version of Altair Hypermesh 2025. The part that will be used is the **intermediate** part of the case study.

F.1 Step 1: Import CAD model into Hypermesh

The first step is to import the relevant CAD model. This is done by navigating to the **File** button in the upper left-hand corner of Hypermesh and then choosing **> Open > Geometry Model** as can be seen in Figure F.1.

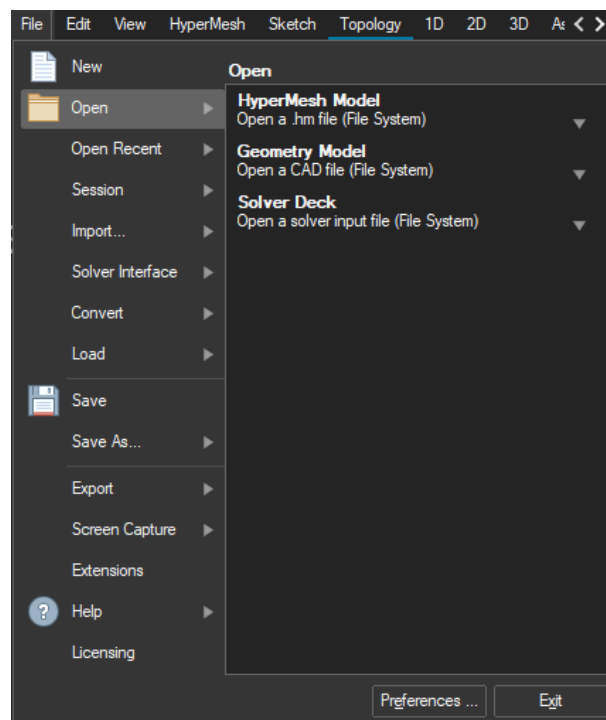


Figure F.1: Importing a CAD file.

Now the user should select the correct CAD file in their directory. After this is done, the **Geometry Open Options** window seen in Figure F.2 pops up. Here several properties of the file can be altered, but the only interesting tab in this case is **Topology**. Here its vital that the correct unit system is selected in the **Target units** drop down menu. If this is not chosen correctly, the conversion between units of the CAD model can be incorrectly converted into Hypermesh, resulting in a larger or smaller model than intended.

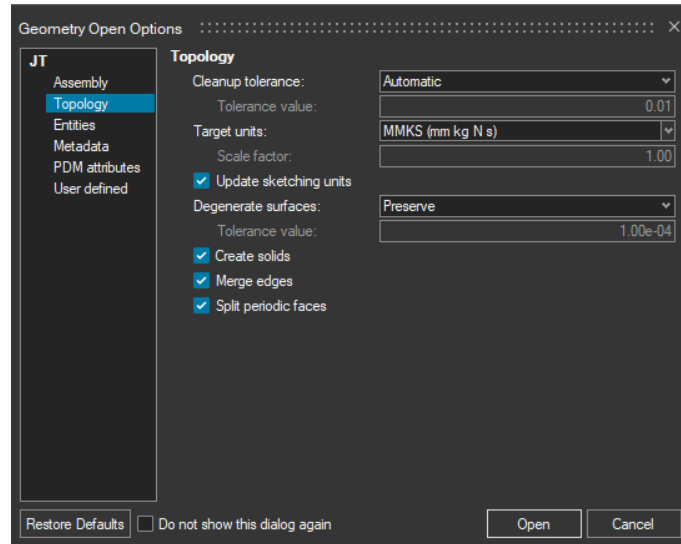


Figure F.2: Selecting appropriate unit.

If prior steps were completed correctly, the CAD model can be seen in the open workspace project.

F.2 Step 2: Creating the mesh

When the CAD model has been imported correctly, it is time to begin the meshing process. There are two ways to do this. In the first, a **midsurface** should be generated using the CAD model. To do this the user should first navigate to the **2D** tool tab seen in the upper part of Hypermesh and then click the **Midsurface** button seen in F.3.



Figure F.3: 2D toolbar with Midsurface tool.

At this stage, continue by first selecting **Automatic** and then **selecting the model**. The model will then become highlighted and a option for selecting solids or surfaces

can be made in the drop down menu seen in Figure F.4. Select **Solids** and then click the **Midsurface** generate button.

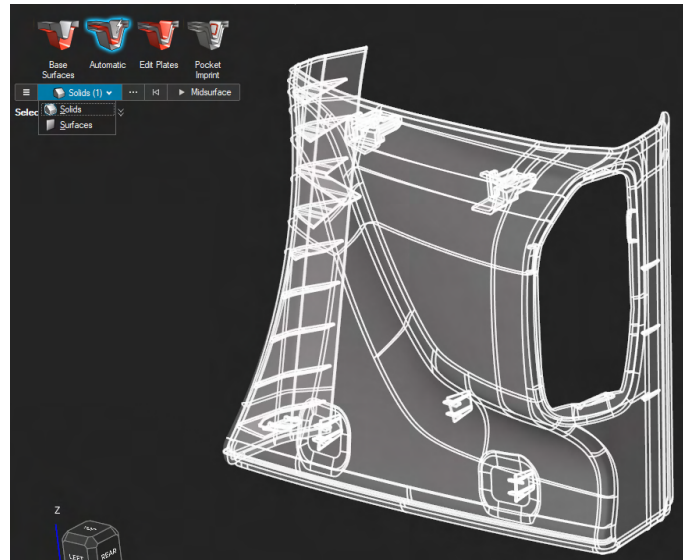


Figure F.4: Highlighted CAD part.

When this step is completed, a midsurface will be generated like the one in F.5. To then mesh this midsurface, the user should use the **Midmesh** tool, which also can be seen in the previous Figure, and **selecting the part** like in previous steps. A popup window with a number and the generate button then appears. This number represents the **size of the mesh elements**.

The other method, which is much easier, works by not performing the **midsurface** steps mentioned earlier and directly using the **midmesh** button. This automatically generates a midsurface and meshes it directly. If one of the methods do not work properly, the other one should be tested.

F. Meshing Procedure

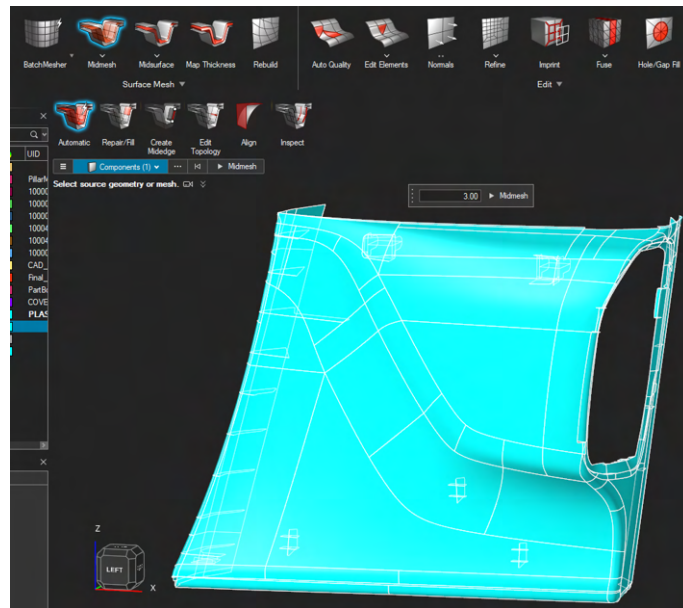


Figure F.5: Using Midmesh on the generated Midsurface.

In the end, if all the steps we have performed correctly, a midmesh should have been generated, similar to the one in F.6. Here the mesh elements are clearly visible.

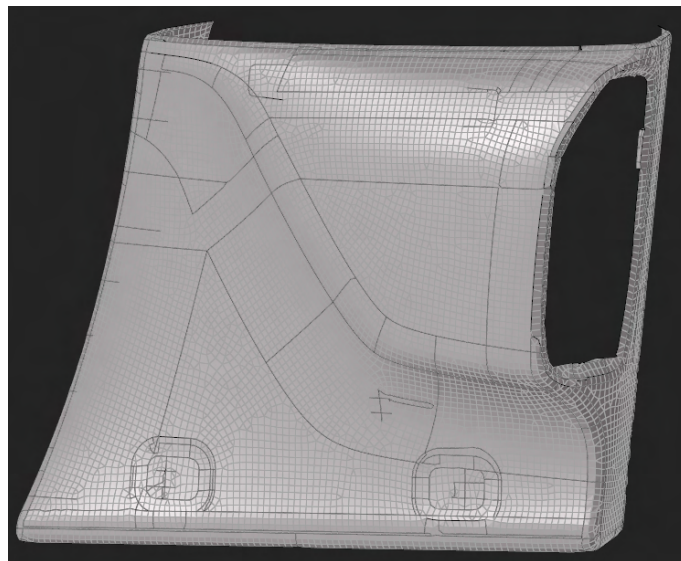


Figure F.6: Midmesh of the intermediate part.

If the mesh is not satisfactory at this point and has, for example, holes or not properly meshed areas, there are many post-processing tools available. These will, however, not be explained in this guide and are left for the user to explore themselves.

F.3 Step 3: Exporting the mesh

Now we move on to exporting the newly generated mesh. Begin by clicking the **File** button in the upper left hand corner. Then navigate through **Export > Solver Deck** seen in F.7. A document navigator then appears where saving the mesh as either **Optistruct**, **Radioss Block** or **Feko** is an option, choose **Optistruct**. The mesh has now been saved and is ready to be used in RD&T.

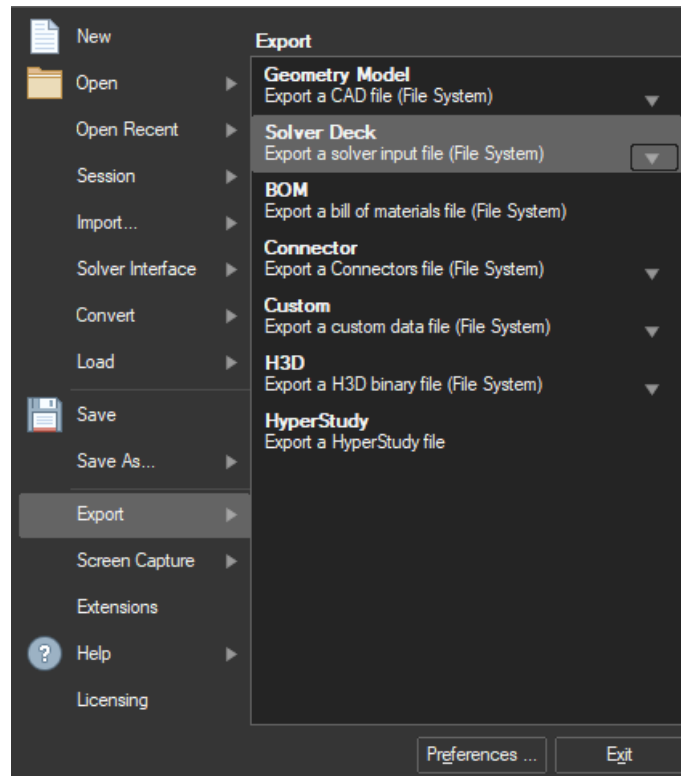


Figure F.7: Export options in Hypermesh.

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