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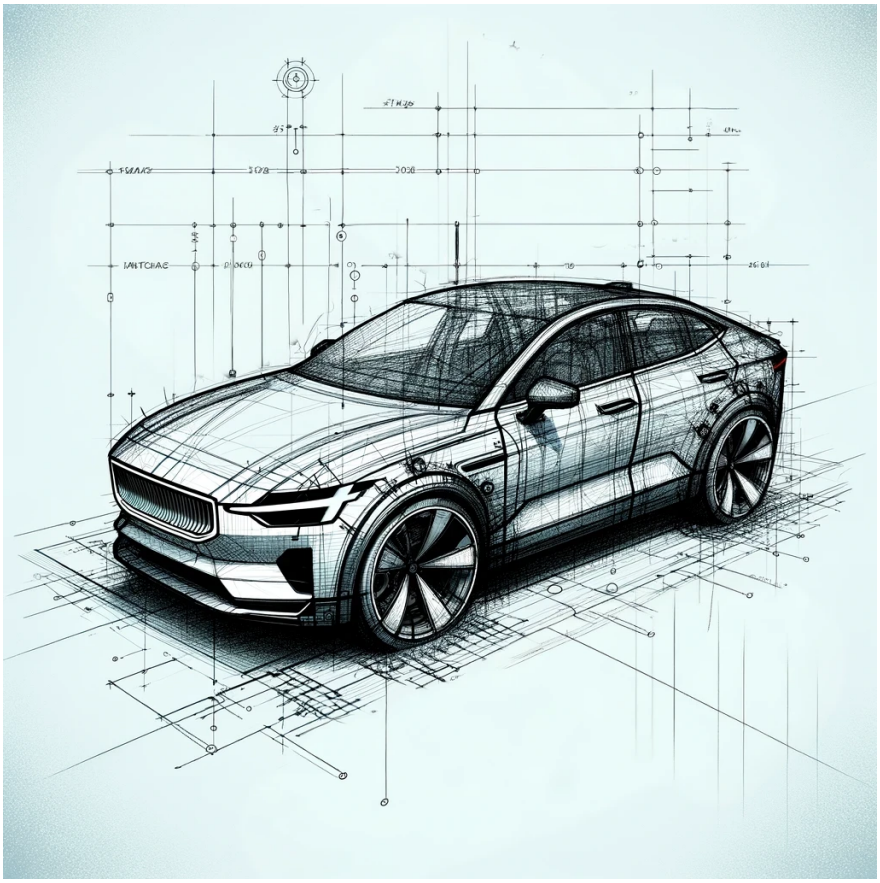

Improvement of Final Demand Data Flow at Polestar

Refining Final Demand Management in the Geometry Assurance Process

Master's thesis in Product Development

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
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Cover: A sketch of a technical drawing of a Polestar vehicle [1].

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Abstract

Geometric variations in components, despite modern manufacturing precision, can detract significantly from a vehicle's functionality and perceived quality. Geometry assurance is crucial for managing these variations by ensuring robustness and high product quality through assigning favorable tolerances. Moreover, efficient data management plays a significant role in geometry assurance, facilitating the necessary exchange of information across various stages of the product realization loop. This thesis focuses on optimizing the data flow and management of final demand data within the geometry assurance process at Polestar, a Swedish automotive company specializing in the production of electric vehicles.

This master's thesis aimed at mapping the current geometry assurance process at Polestar, and by identifying and mitigating inefficiencies, propose improvements for enhancing data quality and process performance. The scope of the study is limited to the geometry assurance process, focusing specifically on the transformation and management of final demand data throughout the distinct phases of the process. Through a literature study, interviews, a pilot study and the mapping of process activities, the current process was studied in detail. The findings reveal significant inefficiencies in the current data flow and process approach. Data flow challenges were predominantly associated with compromised data integrity, as a result of the manual steps involved in data transformation and the propagation of errors due to lack of integration between software tools. Further, the mapping of the current process outlined an approach that often lacks clarity and a solid ground.

The proposed enhancements include the implementation of an API that enables automated data transfer, formatting and storing, eliminating errors associated with manual data exchange across departments and stages. It facilitates communication across three different software programs utilized in different phases of the geometry assurance process, ensuring that the demand data is linked. Through this, data flow efficiency is significantly enhanced and data quality is improved. Further, suggestions intended to optimize the overall performance of the process include implementing standardized work routines and optimizing time management practices. The suggested improvements not only address immediate inefficiencies but also lay a foundation for continuous improvement in data management practices within the company.

Keywords: Geometry Assurance, Data Flow, Process Optimization, Product Realization Loop, Product Development, Final Demands, Robust Design, Tolerance.

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Furthermore, we wish to convey our heartfelt thanks to our examiner, Kristina Wärmefjord, whose insightful feedback greatly contributed to the refinement of this thesis. Lastly, we are deeply appreciative of the unwavering support from our families and friends throughout this journey. Their encouragement has been instrumental in our success.

Gizem Eken and Medina Hamza, Gothenburg, June 2024

List of Acronyms

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

2D	Two Dimensional
3D	Three Dimensional
CAD	Computer-Aided Design
CAT	Computer-Aided Tolerancing
CM4D	Computer Measurement Machine Management Mechanism Data
CMM	Coordinate Measuring Machines
DMIS	Dimensional Measuring Interface Standard
EX	Exterior Demand
FDA	Final Demand Application
FDJ	Final Data Judgement
GA	Geometry Assurance
Geo	Geometry
MBD	Model-Based Definition
ME	Manufacturing Engineering
MP	Measurement Point
PKI	Process Control Instruction
PLM	Product Lifecycle Management
PQ	Perceived Quality
PS	Project Start
QIF	Quality Information Framework
RCA	Root Cause Analysis
R&D	Research & Development
RD&T	Robust Design & Tolerancing Software
SIPOC	Supplier, Inputs, Process, Outputs & Customers
STEP	Standard for the Exchange of Product model data
VP	Verification Production

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1
Introduction

This chapter provides an overview of the background and factors initiating this master's thesis, including a presentation of the company background. The aims and delimitations of the project work are discussed, followed by a description of the research questions intended to be addressed through the work.

1.1 Background

Despite advancements in precision in modern manufacturing processes, geometric variations in physical artifacts occur and are caused by diverse process-related factors, impacting functionality and perceived quality in the final product. A low perceived quality impairs the customer's overall experience and view of the product, which directly correlates to the presence of deviation in the geometry [2]. Companies must address and manage these geometric variations throughout the entire product life cycle by specifying geometrical requirements for the components. Particularly gap and flush requirements are of great importance for the perceived quality of vehicles. Geometry assurance includes a set of activities aimed at managing and reducing the impact of geometric part variations on product quality [3]. It is a crucial part of the product realization process to ensure a design that is insensitive to variation and of high quality, fulfilling final demand requirements.

The electric car manufacturing company Polestar needs to improve the final demand data flow in their geometry assurance process to improve the overall performance of the process, ensuring high standards of quality. Currently, geometry assurance processes for Polestar are carried out in collaboration with PE Geometry, a consultant firm that specializes in geometry assurance. Diverse activities are conducted during the development of a new Polestar car, including geometry assurance. Throughout the geometry assurance process, the engineers at Polestar observe the gradual refinement of the final demand data related to the car's geometry over time, transforming it into other data types throughout the process. Improvement of this demand data management process is required by identifying bottlenecks in the workflow along with integrating potential improvements in the current approach [4]. Thus, this master's thesis was proposed by Polestar together with PE Geometry and will be conducted by two mechanical engineering students from Chalmers University of Technology, during the spring semester of 2024.

1.1.1 Company Background

This section provides background information on the companies involved in the master's thesis, intending to provide an understanding of their history and the work they undertake.

1.1.1.1 Polestar

The company of Polestar is a Swedish automotive brand specializing in the production of high-performance electric vehicles, operating in nearly 30 markets worldwide. The company aims to enrich its customers' lives with cars that integrate Scandinavian minimalist design, high technology, and sustainability. In addition to meeting customer needs, the company aims to achieve "climate-neutral" production by 2030 [5]. This entails reaching zero net carbon footprint in car production, thereby minimizing environmental impact.

The original team of Polestar was initially a motor-sport team founded in 1996 by Jan Nilsson, known as *Flash Engineering*. It later rebranded to *Polestar Racing* when Christian Dahl acquired the team in 2005 [6], establishing an effective collaboration with the Swedish car manufacturer *Volvo Cars*. Their partnership reached a new level in 2015 when it was sold to Volvo Cars. During this time, they agreed to produce cars branded with the Volvo logo but featuring Polestar modifications to enhance performance in terms of speed and power. This model designation became synonymous with their higher-performing cars for the Volvo Car Group [7].

By the end of 2017, the Polestar brand underwent revitalization and was separated from the Volvo brand, although it remained part of the corporation alongside its owner, *Geely Holding*. The company received significant support for initiation through a substantial investment, enabling the establishment of a production site in China [8], with its headquarters in Gothenburg, Sweden. Concurrently, they launched their first product, the *Polestar 1*, an exclusive 600-horsepower electric coupé [9], as seen in Figure 1.1.

Figure 1.1: The Polestar 1 coupé [10].

Since then, they have been actively developing their brand to expand into several global markets by introducing and selling more models, with the Polestar 4 being

their latest launch, an SUV coupé with around 540 horsepower [11].

1.1.1.2 PE Geometry

PE Geometry is a Swedish acknowledged specialist company specializing in the field of geometry assurance, primarily within the automotive industry. They offer their expertise to the industry, such as Volvo Group and Scania Group, and universities through consultancy, research and education. The company is partnered with *NetGroup*, a trusted consultant company for major companies in the automotive industry [12].

The company was established in 1999 in Gothenburg by Peter Edholm to further expand in 2013 to the American market, by establishing its subsidiary in North Carolina. Presently, PE Geometry has offices in Sweden, the US and India [12].

1.2 Aims and Objectives

The primary aim of this master's thesis is to improve the data flow and demand data management in the current geometry assurance process at Polestar, by discerning bottlenecks and proposing strategic improvements to enhance its overall efficiency. Thus, the objectives of the thesis are to study the current process and identify areas of improvement. Additionally, the project objectives include a refinement of the process by integrating enhancements into the existing approach, as well as considering future practice.

1.3 Delimitations

The scope of this master's thesis is constrained by several delimitations to ensure a focused study. Firstly, a notable constraint is the time limit of 20 weeks imposed on the research. Secondly, the study will consider a limited segment of the entire geometry assurance process. Furthermore, the primary focus of this thesis remains on the identification of bottlenecks relating to final demand management within current geometry assurance process. The demand data treated in the thesis includes primarily gap and flush requirements. While the study aims to provide comprehensive insights within the defined time frame, certain aspects beyond these parameters may not be fully explored. The outcome of the project will focus on optimizations and improvements of the current process.

Moreover, the master's thesis will be undertaken by two students holding bachelor's degrees in mechanical engineering. This implies that the scope of expertise may be limited to this field. However, external experts specializing in the relevant areas will be incorporated into the process. Although, there is a deficiency in departments at Polestar, as they lack a unit specializing in perceived quality. This could potentially impose a constraint on the project regarding retrieval of information and knowledge.

1.4 Research Questions

In the light of the aims and objectives of the project, three research questions that are to be answered through the thesis work were specified. These questions are formulated as follows:

1. What is the approach to current practices and documentation methods, including specification and management of demand data throughout the geometry assurance process at Polestar?

2. What bottlenecks are present in the demand data flow of the current geometry assurance process at Polestar?

3. How can the current practices employed in managing demand data in the geometry assurance process be improved, and how can these enhancements be integrated into the existing and future framework at Polestar?

2
Literature Study

In the following chapter, the literature study providing the necessary theory for conducting the thesis work is presented. The theoretical framework covers the key subjects of the project, which are geometry assurance, *GA*, and its function in product design, geometrical requirements and perceived quality, as well as data management in GA processes.

2.1 Geometry Assurance

This section introduces the concept of geometric variation in products, and how GA can be utilized to achieve robust design. It further provides insight into how GA activities are incorporated into the product realization loop.

2.1.1 Robust Design and Geometric Variation

The definition of robust design is a design that is not affected by the presence of variation. The theories regarding geometric variation and robustness in design were originally initiated by Taguchi [13]. Factors that influence variation in a system are categorized as control factors and noise factors. The noise factors are difficult to control, and are external factors that amplify variation, whereas control factors are inputs that regulate variation. The concept of robustness in a system can be visualized using a P-diagram, as shown in Figure 2.1. It demonstrates how different factors affect a product or process, resulting in a response that measures the performance of the system [14].

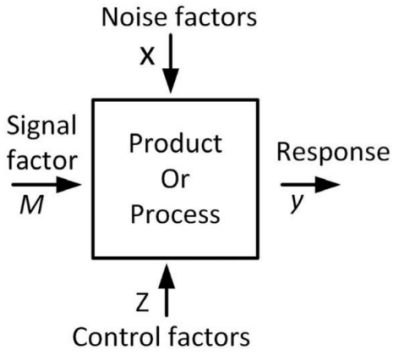

Figure 2.1: P-diagram [14].

The presence of geometric variation and deviation from the nominal geometry in parts can be amplified as a result of additional deviations appearing from physical factors like wear, and thermal expansion. Additionally, variation in critical part manufacturing process parameters or assembly and joining processes can also cause part variation. Consequently, the quality of the product tends to decrease further during use. Hence, there is a demand for companies to control these geometric variations throughout the entire product life cycle [3].

Tolerances serve as a means to specify the allowed variation. Variations on part- and product-level that are not within the given tolerances can impair the final product and fail to fulfill aesthetic and functional requirements [15]. To minimize the presence and effect of variations in a product, a set of activities is conducted to control the geometry. This process is called GA and can be integrated into all phases of the product realization process. The main rule in the field of GA is to avoid introducing additional sources of variation throughout the realization process of the product [13].

2.1.2 Product Realization Loop

The steps of GA can be divided into different phases constituting the product realization loop, aiming to minimize geometrical variations in the designated product. It consists of three phases denoted as concept, verification and production, as visualized in Figure 2.2. Each phase comprises several activities related to the GA process, intending to control the variations in the product's geometry [16].

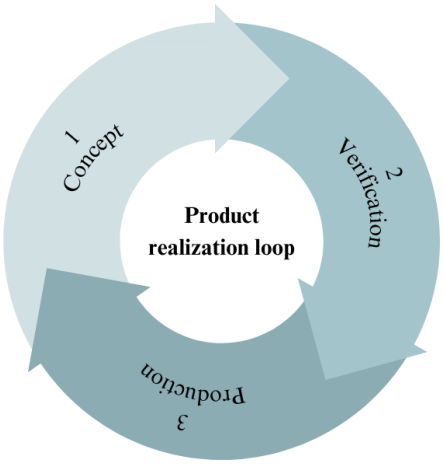

Figure 2.2: Product realization loop. Figure adapted from [13].

2.1.2.1 Concept Phase

In the first phase of the product realization loop, known as the *Concept Phase*, the product and production concepts are detailed. The developed concepts undergo

evaluation to optimize them in terms of manufacturing variation, aiming to control their robustness through the placement of the locators [16]. This implies that no physical product is developed, instead, simulations and data-based testing are conducted to facilitate decisions regarding component separation and manufacturing processes. The tasks related to this phase are summarized as follows [13]:

1. Defining the split-lines to gain an understanding of which components will divide the product.

2. Defining the top-level requirements and their tolerances on the product.

3. Defining the positioning of the locators on the components to increase their robustness, enhancing the product's overall robustness.

4. Allocating tolerances for each part of the product.

The listed tasks are realized by a number of analysis methods, which are briefly presented in Table 2.1.

Table 2.1: Methods used during the Concept Phase. Information taken from [13] and [16].

Name of method	Description
Robust locator design	Robust locator design includes a stability analysis aimed at minimizing variations in components that may occur during manufacturing. This analysis examines locators and their placements, assessing how they influence the stability of critical parts in the product. Through this analysis, different locator designs can be evaluated by varying the positions and analyzing the results.
Locating scheme optimization	Locating scheme optimization is a method for determining the positions of locating points on the product. The objective of this method is to achieve optimal robustness using algorithms.
Statistical variation simulation	The purpose of employing statistical variation simulation is to identify potential variations in crucial parts of the product. The method utilizes two different approaches for tolerance analyses: Monte Carlo simulation-based and deterministic methods.
Part variation estimation and modeling	The estimation and modeling of part variation are conducted in the concept phase due to the unknown variation behavior of the product's parts, as no physical product is assembled at this stage.
Split-line evaluation	Split-lines are crucial factors to assess in the concept phase due to their impact on the quality appearance, also referred to as perceived quality, of the product. Consequently, split-lines are addressed by defining requirements for gap, flush, and parallelism conditions among different parts of the product. These requirements specify distances between parts in various directions. The assessment is conducted through a seam variation analysis, utilizing Monte Carlo simulation and part variation data.
Split-line optimization	Optimizing split-lines on a product can be carried out in cases where locators are predetermined. This is achieved by evaluating the distances of the split-lines on various parts of the product. The purpose of optimizing split-lines is to enhance the overall product quality and achieve a higher perceived quality.
Visualization of variation	The visualization of variation is conducted to enhance understanding of the product and its requirements, utilizing different colors and textures. This process helps easily identify crucial factors, such as locating points or split-lines.
Tolerance allocation	Tolerance allocation is performed during the concept phase to determine the tolerances for each part. By allocating tolerances, the optimization of quality and cost, which are interrelated, becomes possible. This approach enables achieving higher quality at a lower cost than originally anticipated.
Joining sequence optimization	The optimization of the joining sequence is conducted to enhance assembly methods, robustness and quality, given the crucial role of the determined sequence in joining the parts. Typically, this optimization employs a genetic algorithm to obtain the most optimal joining sequence, considering various aspects of the assembly, such as welding gun size or the type of clips used.

2.1.2.2 Verification Phase (pre-production)

The second phase of the product realization loop is the Verification Phase, encompassing activities conducted in pre-production [16]. The objective of this phase is to test and verify the reduced number of concepts developed in the preceding stage, ensuring their practical viability at various points to gather as much information as possible [17]. This phase involves analyses of both the product and the production system, aiming for a seamless transition into full-scale production in the next phase.

Consequently, all inspections, analyses, and tests are conducted to ensure a smooth start to production, including fixing locators and supporting the preparation process [13]. The methods used in this phase include *inspection preparation* and *virtual trimming*, further explained in Table 2.2.

Table 2.2: Methods used during the Verification Phase. Information taken from [13] and [16].

Name of method	Description
Inspection preparation	The inspection preparation encompasses various activities with the goal of identifying and optimizing the inspection points of the designated product. The objective is to facilitate product verification and gather comprehensive information about the process for easier adjustment and correction as needed. This is done by conducting tolerance and robustness analyses, as they provide a broad overview of how the measurements should be carried out. Furthermore, as the verification phase involves analyzing everything in the product before sending it to full production, the number of inspection points can be quite large. For that reason, a method called cluster analysis is used to reorganize the inspection points that are similar into groups, making the verification easier and the process much more effective.
Virtual trimming	Another activity within the verification (pre-production) phase is virtual trimming, which aims to address functional and/or aesthetic issues encountered during the assembly of the developed components. This is achieved by modifying the design, often by changing the location of the locators in a virtual environment for trimming the components that require alterations. Since the software provides immediate results, a physical test is unnecessary when performing virtual trimming. This means that the verification can be conducted based on the results obtained from the software.

Additionally, the variation simulation model can potentially be used as a digital twin, which is a virtual representation of a physical system that allows for real-time monitoring and analysis. By inputting part inspection data into the simulation model, process adjustments can be recommended to optimize geometric quality at the assembly level [18]

2.1.2.3 Production Phase

The third and final phase in the product realization loop is the Production Phase. As the name implies, this phase involves the transition of the product and production concept into full-scale production, utilizing the variation simulation model to manage the production process and identify any occurring problems. Two methods employed during this phase are the Root Cause Analysis, *RCA*, and Six Sigma methodology [13][16], elaborated further in Figure 2.3.

Table 2.3: Methods used during the Production Phase. Information taken from [13] and [16].

Name of method	Description
Root Cause Analysis (RCA)	Root Cause Analysis is a method employed to identify the causes of issues that may arise due to individual fixture errors. During the production phase, this analysis is used to assess the assembly process, which can be categorized into serial and parallel subassemblies based on the product's complexity. For instance, in a serial assembly process, components are assembled in subassemblies. A virtual tool is utilized to conduct the RCA, revealing both variations and deviations. Furthermore, the model in the tool can be updated with inspection data from the final product, enabling an analysis of the assembly and its locators to identify the root cause of identified issues.
Six Sigma	Six Sigma is a methodology utilized to enhance the performance of a process in five steps, with the goal of optimizing efficiency while minimizing costs and maximizing revenues. The method begins with the initial step known as the *Define phase*, where the identification of the process to be improved takes place. The subsequent step is the *Measure phase*, during which the inputs and outputs of the process are precisely defined. The third step, the *Analyze phase*, involves scrutinizing the obtained data to evaluate both inputs and outputs. Moving on to the fourth step, the *Improvement phase* focuses on identifying inputs that exert a significant impact on the outputs and consequently aims to reduce their impact. The fifth and final step, the *Control phase*, is executed to verify the introduced improvements.

2.1.3 RD&T

A tool that is used in GA is RD&T, *Robust Design & Tolerancing*, which is a software for dimensional control, tolerance analysis and statistical simulation variation [19]. This refers to CAT, which stands for computer-aided tolerancing [2]. The toolbox available in the software enables the simulation and visualization of the impact of deviations. This makes it a valuable tool in all phases of the GA process, in advance of the production of physical prototypes. By implementing RD&T in a GA process, robustness and tolerances can be optimized, as well as assembly and joining sequences [19].

Simulating and analyzing the variation is a crucial step in the early development phases of the product realization loop [13]. RD&T allows for statistical analysis and simulation of variation using Monte Carlo simulation. Another common type of analysis that RD&T is used for is contribution analysis, which identifies the contribution of each tolerance that contributes to variation [19].

2.2 Aesthetical Geometrical Requirements

Geometric variation in products does not only impair the product quality and performance but also the customer's experience and perception of the product. Perceived quality, *PQ*, is defined as the customer's visual observation of the quality of the product, which for vehicles primarily relies on the relation between visible components and surfaces [2]. The surfaces visible to the users are called Class A surfaces, whereas the surfaces not visible are termed Class B surfaces [20]. The visual di-

visions between components are called split-lines, which are marked in Figure 2.3. Generally, contact between components in split-lines is not desired. The space that is present in the split-lines are directly affected by the presence of geometric variation in the components. To regulate the space, aesthetical geometrical requirements are specified, indicating allowed maximum and minimum values for the gap and flush-size. Gap refers to the clearance value between two parts, while flush refers to the height difference between the upper surfaces of these parts [21]. If these requirements, also called final demand requirements, are not met, remarkably wide gaps, large flush, asymmetry and non-parallelism may occur in the split-lines, impairing the PQ of the vehicle [2].

Figure 2.3: Split-lines in a Polestar car. Adapted from [22].

2.3 Data Management in the Geometry Assurance Processes

As digitalized production systems and their links across value chains evolve, enhancing efficiency in manufacturing becomes crucial. Additionally, adaptability to constantly changing customer and market demands should be implemented. Thus, data exchange between people, machines, and companies within complex information systems is necessary. This evolution inducing digitalization in product development and manufacturing also generates a change within GA processes and the transfers of demand data. In a GA process, strong links between departments within a company, such as product design, engineering and manufacturing, are crucial. Thus, effective data and information management systems are essential [3].

GA relies on the exchange of data, especially demand data, between different actors in the process. Enhanced capabilities of data storage and transfer facilitate the utilization of demand data in GA. This means that the significance of challenges

related to data quality, data validity, and data security becomes more pronounced. It is important to ensure that the correct data is used to secure the data quality and validity. Thus, an efficient and feasible product data management system that handles all models and data throughout all process activities is of great importance [3].

2.3.1 Application Programming Interface (API)

An application programming interface (API) serves as an intricate coding mechanism facilitating communication between different applications. An application is a form of software designed to enable users to perform specific tasks. APIs provide programs, software, and application developers with precise control over access to application interfaces, without the need for complete shutdown, enabling applications to exchange information in a regulated manner [23].

2.3.2 Industry Standards for Product Data Exchange

As the digitalization trend emerges within manufacturing, a set of industry standards for data exchange between programs and equipment can be utilized to facilitate efficiency. Some of these are the following:

1. DMIS, *Dimensional Measuring Interface Standard*, is a standardized language used for communication of data between computer systems and inspection equipment. It was developed with the aim to transfer files from CAD systems without altering the data through translation or restructuring. DMIS provides a common interface allowing programs to be run on different CMMs, coordinate measuring machines, which ensures significant flexibility for manufacturers [24].

2. STEP AP242, *Standard for the Exchange of Product model data*, is an international standard that defines how to represent 3D mechanical product data in a neutral format, facilitating exchange between diverse CAD software platforms. It encompasses various aspects of product data, including geometry, assemblies, annotations, and metadata [25].

3. QIF 3.0, *Quality Information Framework*, focuses on quality-related information associated with manufacturing processes and inspection activities. It provides a standardized approach to represent dimensional and geometric tolerances, inspection plans, measurement results, and other quality-related data. For example, within QIF files, requirement fulfillment statuses for individual measurements can be stored and retrieved, directly linked to the respective features [25].

4. MBD, *Model-Based Definition*, is a method that employs a shared 3D model of the product or production system throughout its development and life cycle. Through the implementation of MBD, manual labor and reliance on hu-

mans can be reduced, enhancing efficiency while minimizing the risk of errors. This implies numerous advantages regarding both cost-effectiveness and operational efficiency in manufacturing processes. For instance, the definition can be utilized to show that 2D drawings can be exchanged with 3D models or to automate data handling. [25].

2.4 Benchmark of Data Management in Geometry Assurance Processes at Competing Companies

This section presents the data management methodologies in GA processes at Volvo Cars and Zeekr, formerly known as CEVT. By comparing and presenting these companies' approaches, insights into strategies, tools and challenges can be identified.

2.4.1 Volvo Cars

The GA process at Volvo Cars runs through four phases denoted as *Concept Phase, Engineering Phase*, followed by *Industrialization Phase* and finally *Production Phase*. There are several milestones and gateways present in the process, including design releases termed *Digital Surface Model* releases, or DMS-releases. These gateways are named DMS0, 2, 3, 4 and 5, which are iterations leading up to FDJ. FDJ stands for *Final Data Judgement*, which is a gateway indicating cross-functional confirmation that the final demands are fulfilled [26].

The process of defining FDR, *final demand requirements*, is initiated at the PQ department. RD&T is used to create PQ documents and *SharePoint*, which is a software part of the Microsoft package used to simplify collaboration and sharing of data [27], is utilized for tracking requirement data. The site in SharePoint where the requirement data is gathered is called the *Geometry Scorecard*, which supports the formation of the PQ documents. Additionally, another site called the *Masterlist* is available in SharePoint for storing old requirement data [26]. The reason behind storing old data lies in the ongoing discussions that alter the requirements throughout the process, resulting in deviations from the original specifications. These changes are documented either in RD&T or in SharePoint [20]. RD&T is utilized for assigning tolerances, calculations and managing requirements. Further, measurement preparation is carried out [26].

Volvo Cars has implemented a system called *FLOW*, used to document any issues identified and highlighted during summaries. The process involves creating, naming, and assigning tasks for PQ sections, with standardized templates and priority scales for the organization. It includes assigning tasks to responsible engineers, tracking progress with workflow statuses, and notifying interested parties. Problem Reports are created for issues, linked to tasks, and communication is facilitated through comments. Finally, during running production, GA is carried out in order to ensure that the FDR is fulfilled throughout the entire life cycle of the vehicle [26]. In this phase,

the software CM4D is used, which is a dimensional analysis tool for manufacturing processes [20].

2.4.2 Zeekr

The GA process at Zeekr is initiated through the specification of PQ requirements. Benchmark of competing companies' products is carried out to set a standard for the level of PQ. RD&T is utilized for GA activities. Further, PLM systems *TeamCenter*, and *SystemWeaver*, softwares for managing products or systems throughout their lifecycles, are utilized for managing part models and requirement data. Both SystemWeaver [28] and TeamCenter [29] are software used to manage the specification of software components and systems on a shared platform. A shared PowerPoint file is used by the PQ and GA team to track activity and changes [30].

Iteration and looping is a crucial part of the process at Zeekr. GA engineers are provided with feedback and perform calculations on the construction. Regular check-ins are arranged weekly with different teams [30].

3
Methodology

This chapter provides a description of the designated work process and the methods utilized, along with the motivation behind the chosen methodology.

3.1 Methodology Approach

To improve the data flow, with a focus on final demands, within the GA process at Polestar, it is crucial to have understanding and support. These are derived from design research conducted using a specific methodology. To support the thesis work, the methodology will be based on the design research presented in [31] with adaptations, aiming to improve the design process, which aligns with the objective of this master's thesis.

Firstly, the design research methodology, *DRM*, from [31] initiates with a research clarification. This step aims to extract information and data from the literature study findings, aiding in addressing the research questions of the master's thesis. Additionally, it provides clarity on the current situation of the organization, supporting the subsequent steps.

Next, the second step involves initiating the first descriptive study. Despite collecting sufficient literature and specifying objectives, the research questions remain unanswered. Therefore, descriptive study 1 is employed in the methodology to broaden understanding and gather more information through interviews. This empirical data gathering is essential to enhance comprehension before progressing to problem identification and improving the current process.

The third step presented in the DRM from [31] is the prescriptive study. In this phase, it is crucial to utilize the outcomes from the preceding steps to assess the current process and subsequently enhance it. This involves identifying problems within the current process to enable improvement and optimization.

The fourth and final step outlined in the DRM from [31] is the second descriptive study. This step is where the improvements are implemented. However, as the implementation falls outside the scope of the master's thesis' objective, this phase will only analyze the outcomes from the prescriptive study and thereafter provide recommendations for implementation to the company and its future work.

The DRM will therefore be adapted and divided into three key phases, termed as *Preparation, Realization* and *Analysis*, each containing a set of activities. The adapted DRM is depicted in Figure 3.1 below.

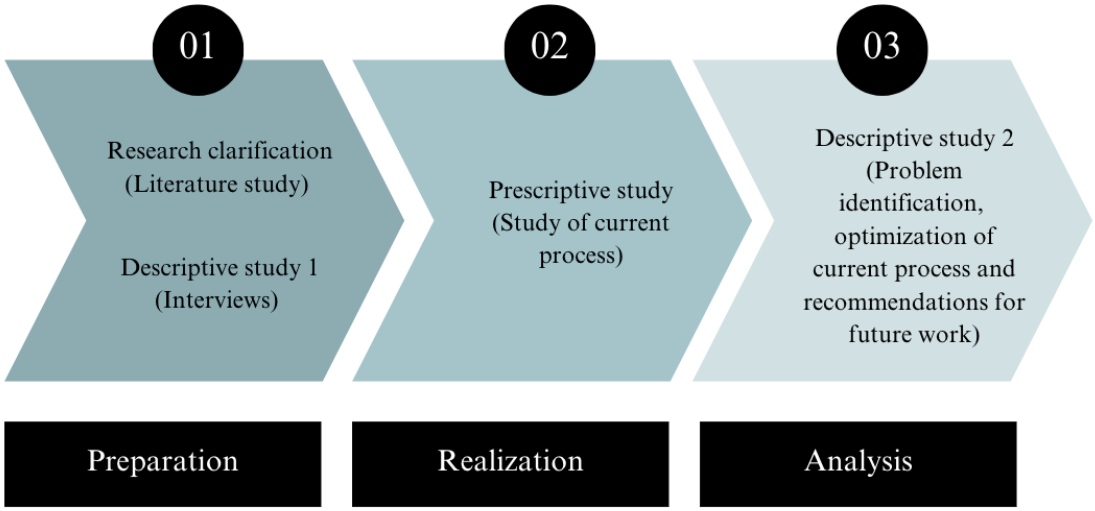

Figure 3.1: Methodology approach.

3.2 Preparation Phase

The Preparation Phase includes a literature study and interviews with individuals currently engaged in GA processes, both within and outside Polestar. This was conducted in order to gain a thorough comprehension of the subject prior to the Realization Phase, laying a meticulous foundation for the planned work.

3.2.1 Literature Study

The literature study was conducted with the purpose of gathering relevant and useful material serving as a theoretical framework for the thesis work. In order to ensure the best outcome of the project, a selection of the essential and most significant information was found and studied. The selection of subjects included in the study was done with the aims and objectives of the thesis as a basis, assuring that the theoretical framework necessary for conducting the thesis work was covered. The gathering of data and information was performed using online based search engines, preeminently the *Chalmers Library database* and *Google Scholar*. Academic papers and literature were the primary sources from where the information was obtained, which were found using relevant keywords related to the sought theory.

3.2.2 Preparatory Interviews

Preparatory interviews were conducted to gather qualitative data and gain an understanding of the current GA process at Polestar. Qualitative data collection is defined

as a research method that emphasizes understanding and interpreting phenomena through in-depth analysis of subjective experiences, perspectives, and social processes [32]. A qualitative research approach was selected to obtain a more in-depth, contextual understanding of the participant perspectives, and generate descriptive research data.

The preparatory interviews were planned as semi-structured interviews, leading to the creation of an interview guide with a predefined set of relevant questions related to the work and its challenges, as outlined in Appendix A. Semi-structured interviews are a qualitative research approach used to gather data and information from interviewees in a controlled yet conversational manner. While there is a predefined set of questions, there is room for room for follow-up questions and flexibility within the interview [33]. The preparatory interviews were conducted after obtaining information from supervisors and professionals within the company, who assisted in selecting the relevant interviewees. Subsequently, the selected interviewees were contacted to schedule a meeting time that would suit their agendas.

The interviews followed a chronological order, with the interviewee representing the Concept Phase being interviewed first. The interviews took place both digitally and on-site, depending on the availability of the interviewee. Since the interviews were semi-structured with a predefined set of questions, they were asked to the interviewee in a chronological manner. However, room was left for additional questions that could enhance the answers provided during the interview. To facilitate the transcription of the answers, the interview was recorded. The transcribed answers obtained from the interviews were gathered and structured in an Excel sheet.

3.2.3 Interviews with Engineers from Competing Companies

Additional interviews were conducted with engineers from competing companies to gain qualitative data on their GA process and compare it to the one at Polestar. These interviews provided a solid foundation for obtaining information on specific topics through a qualitative research approach, particularly their perspectives on how PQ impacts the GA process.

The interviews were meticulously planned and executed in a semi-structured format. This approach involved a set of predefined questions, as outlined in Appendix B, with flexibility for addressing any additional questions that might arise during the interview. Moreover, the interviews were recorded to facilitate the transcription process.

3.3 Realization Phase

The Realization Phase involves a comprehensive examination of the current process employed at Polestar, encompassing all stages from the initial phase to the final one, with the results obtained from the preparatory phase in mind. This was partly done by conducting a simplified version of the actual process, which means that a much smaller amount of demands and correlating components were examined instead of the whole vehicle. Additionally, in-depth interviews were conducted with relevant engineers to delve deeper into the workflow and enhance the understanding of issues encountered during the examination. The objective was to map the process on a more detailed level, along with identifying both positive and negative aspects of the current process at Polestar, thereby facilitating results for the analysis phase.

3.3.1 Study of Current Process

The current process was assessed by studying real documents from ongoing projects, conducting a simplified version of the process and conducting in-depth interviews with involved engineers within the company.

3.3.1.1 Mapping of Current Process

To be able to comprehensively map the current process along with its phases and incoming activities, the preparatory interviews, see Section 3.2.2, were complemented by conducting in-depth interviews with engineers within the company. Utilizing the insights obtained from these interviews, a flow chart was created to depict the current process, emphasizing both the activities and data flow.

In-depth Interviews
In-depth interviews were conducted to deepen the initial understanding of the current GA process and to fill in the gaps in the qualitative data previously gathered from the preparatory interviews. Similarly to the previous interviews, the in-depth interviews were also approached using a qualitative research approach to gain detailed insights into the participants' perspectives.

The in-depth interviews were individually tailored for each participant and structured in both a semi-structured and an unstructured format. The semi-structured interview resulted in an interview guide containing a predefined set of questions, whilst there was no preparation for the unstructured interview. An unstructured interview aims to keep the interview open-ended to facilitate flexibility and nuanced answers from the participant by asking descriptive questions that do not disrupt their narration [34].

The interview guide for the semi-structured interview was customized based on the participant's role and involvement in the product realization loop, as detailed in Appendix C. While the interview adhered to the chronological order of the predefined questions, there was flexibility to ask additional questions as they arose during the interview. Since the participants resided abroad, the interviews were conducted

digitally and recorded to facilitate transcription.

3.3.1.2 Process and Data Flow Diagram

To graphically represent the process and data flow of the current process, a flow diagram was created using the tool *Mural*, a versatile platform utilized for generating various types of diagrams. The flow diagram was developed iteratively and continuously updated throughout the study of the current process as more information was obtained. Various symbols and line styles were thoughtfully selected and incorporated to enhance readability and simplify comprehension for the reader.

3.3.1.3 SIPOC Diagram

With the entire process and data flow charted, a SIPOC diagram was created in order to obtain an overview perspective of the process. SIPOC stands for *Supplier, Inputs, Process, Outputs* and *Customers* [35]. It is a tool used to map these elements of a process, which provides a comprehensive understanding of the entire system, ensuring no critical element is disregarded. The purpose of using a SIPOC diagram is to provide a holistic overview of a process and its most crucial parts. This helps identify bottlenecks and inefficiencies, highlighting areas in need of improvement. Additionally, by examining suppliers, inputs, processes, outputs, and customers, teams can identify potential bottlenecks or inefficiencies within the current process.

3.3.1.4 Pilot Study

The initiation of the simplified version began with the acquisition of necessary documents, files and software access. This process involved submitting an access request through Polestar's internal service portal and requesting access for utilizing components. While awaiting approval, an examination and analysis of the exterior demands' requirements documentation took place. Two demands, including gap and flush requirements, were selected for use in the simplified version.

Upon selecting the demands and their corresponding components, additional approval was sought to be able to use them in the thesis work. Once granted, the Pilot Study was conducted according to the current designated work process at Polestar. The work was carried out in three phases, structured as *Concept Phase, Verification Phase* and *Production Phase*, as presented in Section 2.1 of the literature study.

3.4 Analysis Phase

The Analysis Phase entails an examination of the current process, commencing with a comprehensive analysis of interviews and the Pilot Study. Through content analysis of interviews and Pilot Study findings, the aim is to gain valuable insights into the facets of the current process, identifying both strengths and areas for improvement. Additionally, the phase involves an intensive brainstorming session aimed at

generating innovative solutions for optimizing the data flow. This includes brainstorming sessions dedicated to determining the placement of solutions within the data flow and employing the 5 Hows Method to delve deeper into solution details. The objective is to devise practical and effective strategies for enhancing the efficiency and effectiveness of the final demands management in the GA process at Polestar. Furthermore, suggestions for refining the process flow are formulated based on the insights garnered from the analysis.

3.4.1 Analysis of Current Process

This section encompasses a thorough examination of the existing processes, conducted through two main approaches: content analysis of conducted interviews and analysis of the Pilot Study. These analyses serve as a foundation for further analyses, providing crucial insights that inform subsequent stages of the methodology.

3.4.1.1 Content Analysis of Interviews

The compiled sheet containing the transcription of all conducted interviews was used as a basis for examining the answers by utilizing *content analysis*, which is a technique used with the aim to identify patterns and common themes within qualitative interview data [36]. Prior to analyzing the answers, a guiding scheme defining significant themes and implications was defined to facilitate the identification of patterns among the answers. According to a content analysis-based method, a pre-defined scheme can be used to categorize responses into themes or concepts, which allows for systematic analysis and comparison [36]. The aim of the content analysis was to identify facets of the current process among the respondents' answers, in order to obtain an understanding of what improvements are necessary. The key takeaways from the answers were summarized in a table.

3.4.1.2 Pilot Study Analysis

The Pilot Study was conducted to gain firsthand experience with the execution of the GA process and to identify and document ineffective bottlenecks as well as other facets of the process. Throughout the Pilot Study, identified bottlenecks were documented for each step, concurrently with the initial flowchart being updated to reflect activities. Mapping the process flow facilitated the identification of bottlenecks, making it clearer where improvements were needed within the flow. The Pilot Study was iterated to enable more in-depth identification of bottlenecks with each iteration. For analyzing the interview answers, as detailed in Section 3.4.1.1, content analysis was utilized to examine the identified bottlenecks. The purpose of employing content analysis was to discern improvement areas and detect patterns among the process activities [36]. The key findings were synthesized and presented in a table.

3.4.2 Brainstorming of Solutions for the Data Flow

To generate solutions for the problems concerning the data flow, a brainstorming technique was utilized. Brainstorming is a method used to produce creative ideas for identified problems, either in smaller or larger groups. There are various types of brainstorming techniques, in this case, both traditional and nominal brainstorming were utilized to generate solutions ideas [37]. The brainstorming session was initiated with a nominal approach, where group members individually generated ideas and recorded them on Post-it notes. Facets from both the interviews and Pilot Study were used as a basis. Subsequently, a traditional brainstorming session commenced, during which members collectively discussed and generated qualitative ideas using a whiteboard. After identifying the solutions, their placements within the data flow were determined. Subsequently, the 5 Hows method, adapted from the 5 Whys method, was employed to elaborate on these solutions, as presented in the following sections.

3.4.2.1 Placement of Solutions in the Data Flow

The first step of the solution formulation was to locate particularly critical areas in the process. This was done separately for the data flow and process-related improvement areas, as these two aspects are addressed with different solutions. For process related issues, the findings from the analysis of the interviews and Pilot Study were directly used as a basis.

For the data flow, the flowchart was studied. The data transfer in each step of the process was observed and evaluated in terms of efficiency and preservation of data quality. The steps in the data flow that were assessed to be the most critical were marked with red, indicating that these areas are in need of a solution. Additionally, the placement of the solutions that were to be determined later in the process was specified in the flowchart.

3.4.2.2 The 5 Hows Method

Once the solution areas were identified, determining how the solutions would function was crucial. To address this, the 5 Whys method was utilized, a technique commonly used to identify root causes of problems [38]. In this case, the method was adapted to suit the outcomes of the brainstorming session, where the 5 Whys were employed as 5 Hows to determine how the solutions would operate in detail, as depicted in Figure 3.2.

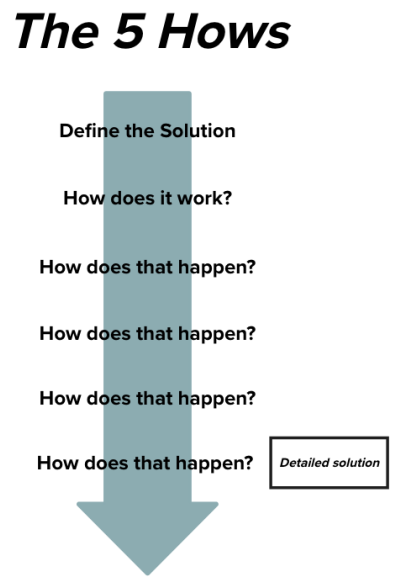

Figure 3.2: The 5 Hows. Adapted from [38].

The solution was approached following the direction of the arrow depicted in the figure above. Initially, the solutions were defined to later uncover answers to questions regarding how it works and how it happens, ultimately obtaining a sufficiently detailed solution. This solution was then visualized in the form of black boxes with inputs and outputs, using the tool *Mural*. The black boxes aim to provide a visualization of how the solution works by showing where the input and output go in the data flow.

3.4.3 Suggestions for the Process Flow

To address process-related problems, the analysis of interview responses and insights gained from the Pilot Study served as the foundation for a content analysis. The objective of this analysis was to pinpoint common problem areas and patterns obtained from these activities, compiled in an Excel spreadsheet for easier reference. The outcome of the content analysis clarified areas in need of improvement, indicating where enhancements were required. The results were presented in a list.

To tackle these improvement areas and devise suitable suggestions for solutions, the 5 Whys method was adapted into the 5 Hows method, as elaborated in Section 3.4.2.2. The purpose of employing this method was to provide detailed insights into how each improvement area could be effectively addressed. Additionally, the identified strengths and potential improvements obtained from the interviews were used to generate the solutions. The key findings were summarized in a table.

4
Results

This chapter presents the results generated from the various activities conducted in the Preparation, Realization and Analysis phases. It demonstrates the current process, mapped using the results from the interviews, Pilot Study and from studying the process activities. Finally, the facets identified within the process and the solutions addressing them are presented, along with a proposed process with the solutions integrated.

4.1 Current Process

In this section, the results obtained from studying the current process are presented as a detailed explanation of the workflow. This includes the results from the interviews, the mapping of the activities and data flow in the process, and a description of the execution of the Pilot Study. Further, a graphical representation of the process is provided.

4.1.1 Interviews

The findings derived from the interviews are outlined in this section, presenting the outcomes of the preparatory and in-depth interviews.

4.1.1.1 Preparatory Interviews

The interviewed engineers within the company are part of the R&D Geo *Research and Development - Vehicle Integration and Geometry* team and the ME Geo, *Manufacturing Engineering - Geometry* team. Both of these departments are involved within the GA process to a great extent, and manage the final demand data in some way. The engineers taking part in the preparatory interviews were the following:

- GA Engineer at the R&D department in Coventry, the United Kingdom.
- Geo Program Manager at the ME department in Gothenburg, Sweden.
- Geo Engineer at the production facility in Chongqing, China.
- Geo Equipment Engineer at the production facility in Chongqing, China.

Each conducted interview lasted approximately one hour, and the transcribed answers for each participant can be found in Appendix D.

The results obtained from the content analysis of the interviews imply that there is a pattern present among the answers of the respondents. Based on the descriptions of the respondents' work processes in the respective phases, an initial, brief mapping of the process flow could be done, which can be seen in Figure 4.1. A presentation and analysis of the key findings from the interviews are presented in Section 4.2.1.

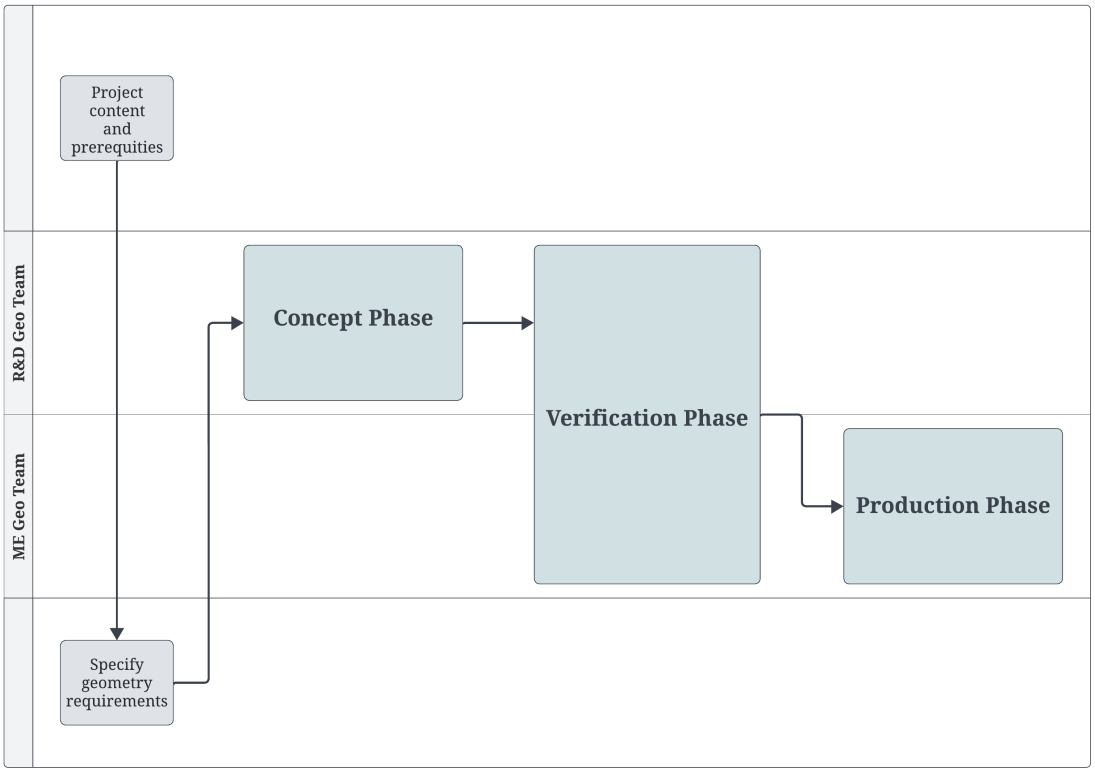

Figure 4.1: Initial mapping of process flow.

The larger light green colored areas represent different phases in accordance with the product realization loop, see Section 2.1.2. Each row represents the responsible team for that phase. For instance, the Verification Phase extends over two rows meaning that the responsibility is split between the R&D Geo team and ME Geo team.

4.1.1.2 In-Depth Interviews

The following engineers from the company participated in the in-depth interviews:

- Senior Geo Engineer for Vehicle Integration and Geometry team at the R&D department in Coventry, the United Kingdom.

- Geo Engineer at the ME Geo team in Chongqing, China.

The in-depth interviews each lasted approximately one hour and the transcribed responses for the semi-structured interview can be found in Appendix E, whilst the responses from the unstructured interview were not recorded and instead used to perform the Pilot Study.

The content analysis of the results revealed a detailed understanding of how each phase within the GA process operates. This insight facilitated further enhancement and updating of the process flow mapping, as depicted in Figure 4.2.

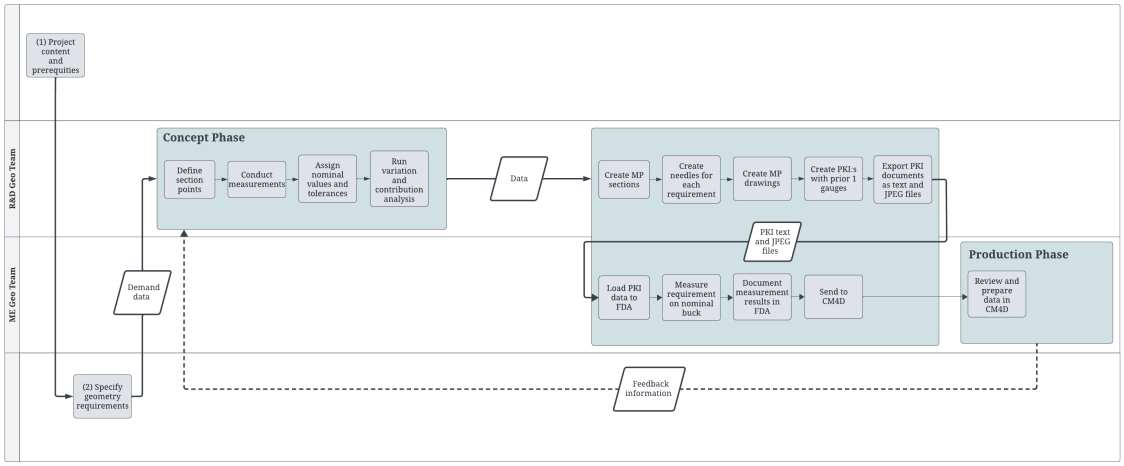

Figure 4.2: Updated flow chart of the final demands management in the GA process.

The flow chart realizes the process activities and data flow between different phases and departments. The data transfers are visualized through white parallelograms, while the activities within the distinct phases are visualized through light grey rectangles.

4.1.2 Mapping of Current Process

The phases within the product realization loop are also evident within the Polestar organization, with different departments working in various stages. However, findings from the study of the GA process, along with content analyses from the various interviews, imply that the phases within Polestar are not as clearly defined as they are in the literature study, which is presented in Section 2.1.2. The results of the mapping will be presented in the following subsections.

4.1.2.1 Concept Phase

The study results and insights from various interviews indicate that the Concept Phase of the final demands management within the GA process is overseen by the Vehicle Integration and Geometry team, a component of the R&D department. The Geo Engineers within this team closely collaborate with the requirements and final

demands, engaging in calculations of the requirements and their tolerances.

The Concept Phase of the current process commences upon the delivery of the vehicle design and engineering models with demand data from the Design Engineers in the R&D Engineering team. This delivery comprises CAD information, representing the vehicle's geometry, both A and B surfaces, along with material details for the vehicle parts. The CAD files are manually imported into the designated CAT software, RD&T. Concurrently, the R&D Geo team manually creates an Excel sheet known as the *Gap Plan*, which outlines the vehicle's specifications, including dimensional attributes such as final demands including tolerances. Additionally, the team is tasked with analyzing the Gap Plan to determine the target values for visual appearance and functional requirements, as part of dimensional engineering. This activity is conducted iteratively.

Once the CAD files are imported into the RD&T software, several in-software steps are initiated. Firstly, the model is prepared and built by positioning the CAD parts according to reference system and assembly process, while simultaneously updating the Gap Plan. Thus, the Geo Engineers also work on the vehicle's aesthetics since there is no PQ department in Polestar. However, they do not have final ownership of the PQ demands. The assessment of tolerances affecting the vehicle's appearance is either discussed with the team or determined based on individual expertise during the vehicle dimensioning process. Further, this allows for conducting various simulations, such as variation or contribution analyses, based on the type of final demand and the desired output of the engineer. The subsequent steps in the software are managed by the same team but are part of the next phase of the GA process, which will be presented in the next section. The results of the analyses can be iterated based on outcomes, in such cases, the simulation is conducted once again with modifications and optimizations until the desired outcome is reached. In other cases, when optimization or justification is not possible, the demand or design can be balanced. A balancing is carried out to determine whether the demand or design needs modification.

Simultaneously, another activity takes place, known as ad-hoc design assistance, which can be outside of the actual work process. This involves providing dimensional assistance to Design Engineers, from the R&D Engineering team, as needed. When Design Engineers require dimensional assistance, they often send reflections or CAD files via email, to get evaluations for their thoughts or to determine which performs best from a dimensional standpoint. In these cases, the CAD files or reflections are circulated internally and the analysis is conducted to provide feedback directly to the Design Engineer.

4.1.2.2 Verification and Production Phase

The results obtained from studying the current process indicate that there is not a clear, distinct barrier between the Verification Phase and the Production Phase of the current process at Polestar. The transition between the phases is merged as the ME Geo team and R&D Geo team are involved in both and integrate the two

processes through their work. Thus, the results obtained from studying the phases will be presented jointly.

The Verification Phase is initiated through the final task of the R&D Geo team, which is to conduct an *inspection preparation* in RD&T. Inspection preparation involves identifying the necessary measuring points, or *MP:s*, for validation of the specifications outlined in the product drawings. Defining MP:s at each level, component, sub-assembly, assembly, and final product is crucial for ensuring precise verification of the product quality [39]. Subsequently, PKI, *process control instruction*, drawings are created to provide operators with instructions on how to conduct measurements of the gap and flush demands by specifying the nominal values and tolerances. This also includes a measurement tool, a digital gauge, that is imported to RD&T and placed appropriately. The outputs from RD&T are part drawings in the form of JPEG files with outlined MP:s and sections, and text files containing input data for the following step.

With the inspection preparation completed, the inspection and measurement of the defined gap and flush demands can be carried out. The data obtained from the inspection preparation is handed over to a Geo Engineer in the ME Geo team. The inspection activities are defined in a control plan, which is used as a basis for the measuring process. Firstly, a project containing the PKI drawing and data from the inspection preparation is created in a software called FDA, *Final Demand Application*, used for part verification. The current project is assigned in the interface and the site where the measuring is carried out is specified, usually at the production facility in Chongqing, China. Using a calibrated gauge for measuring, the nominal gap and flush demands specified in the PKI are measured by an operator on a vehicle or nominal buck, depending on the project's status. A nominal buck is an aluminum hardware that serves as a conversion of the CAD models of the parts. It is a tool used for analysis and verification of the part geometry with interchangeable parts to be able to analyze production parts in a nominal environment, utilized among other tools for decision-making on demand or construction changes.

In some cases, the outcome of the part verification may indicate that new PKI:s are necessary. The reason for this might be that the specified digital gauge selected in the inspection preparation was not fit for the part verification. This feedback information is then sent back to the R&D Geo team who iterates the update of the PKI:s.

The results from measuring the demands on the vehicle or nominal buck are documented by a Geo Engineer in FDA. The field will be displayed in different colors depending on whether the deviation of the measured value falls within the specified tolerances. The results are automatically exported to CM4D, *Computer Measurement Machine Management Mechanism Data*, a database used for storing and analyzing data, from FDA. Once the data reaches CM4D, it is stored and utilized for analysis of the measurements. The CM4D tool does not generate any further output flow, marking the end of the data flow within the scope of the study.

The demand that was not within the specification and thus turned red is managed in *PIRA*. PIRA is a portal used within Polestar to report on product or process-related issues identified in product projects. In order to meet the final demands, an applicable action needs to be carried out for the unmet demand. One of the options is to modify the demand, which implies that feedback on the results is communicated back to R&D Geo team where the demand can be changed. To decide on an appropriate action, several different methods can be utilized to support the decision. A common practice is to identify the root cause of the demand not being within specifications, which can facilitate addressing the issue. This is termed *Root Cause Analysis*, or RCA, and is performed by the R&D Geo team and ME Geo team.

4.1.3 Significant Gates in the Current Process

In the current process, several key milestones are navigated within the scope of the study. These include the project start, *PS*, representing the commencement of the vehicle program and the formulation of project requisites necessary for advancement to the current process; the final data judgment, *FDJ*, representing the completion of the vehicle design for verification purposes, signifying no further alterations required; and the prototype builds phase, *VP*, wherein prototype production begins to verify previous calculations on a complete vehicle before commencing mass production.

To summarize, the PS marks the initiation of the car program, allowing for the establishment of necessary project requirements. The FDJ stage indicates the completion of design verification with no further adjustments necessary. Finally, the VP entails the commencement of prototype production to validate previous calculations before proceeding to full-scale production.

4.1.4 Graphical Representation of the Current Process

This section provides a visual representation of the current process through a detailed presentation of a process and data flow diagram. Subsequently, a comprehensive narrative elaborates upon the activities of the depicted process, enhancing understanding of the work flow. Additionally, a structured SIPOC diagram is included to further illuminate the process and to provide a simplified overview of the complex process flow.

4.1.4.1 Process and Data Flow Diagram

The outcomes derived from the process and data flow are documented in Appendix F. The diagram successfully illustrates the activities within the three phases, incorporating interconnected data flows between them, alongside details indicating the responsible department for each phase or activity. The different types of symbols and line styles indicate various items, which also is explained in Figure 4.3 below.

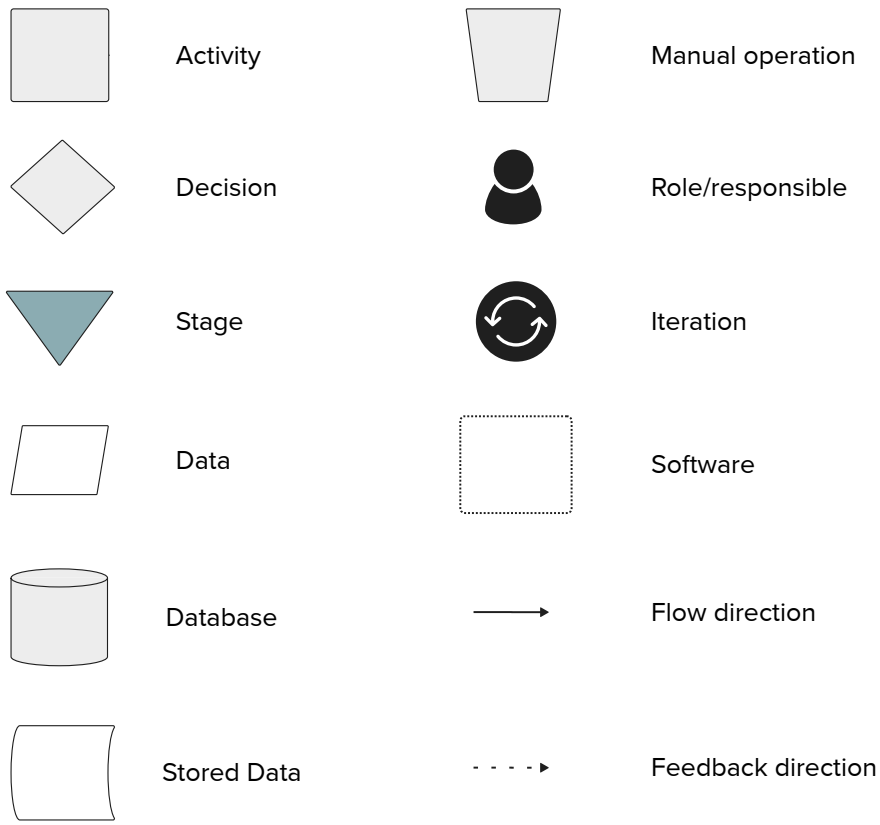

Figure 4.3: Description of symbols and line styles used in the flow diagram.

The initial segment of the comprehensive diagram illustrates the activities between the PS and the FDJ including the ones within the Concept Phase, as depicted in Figure 4.4.

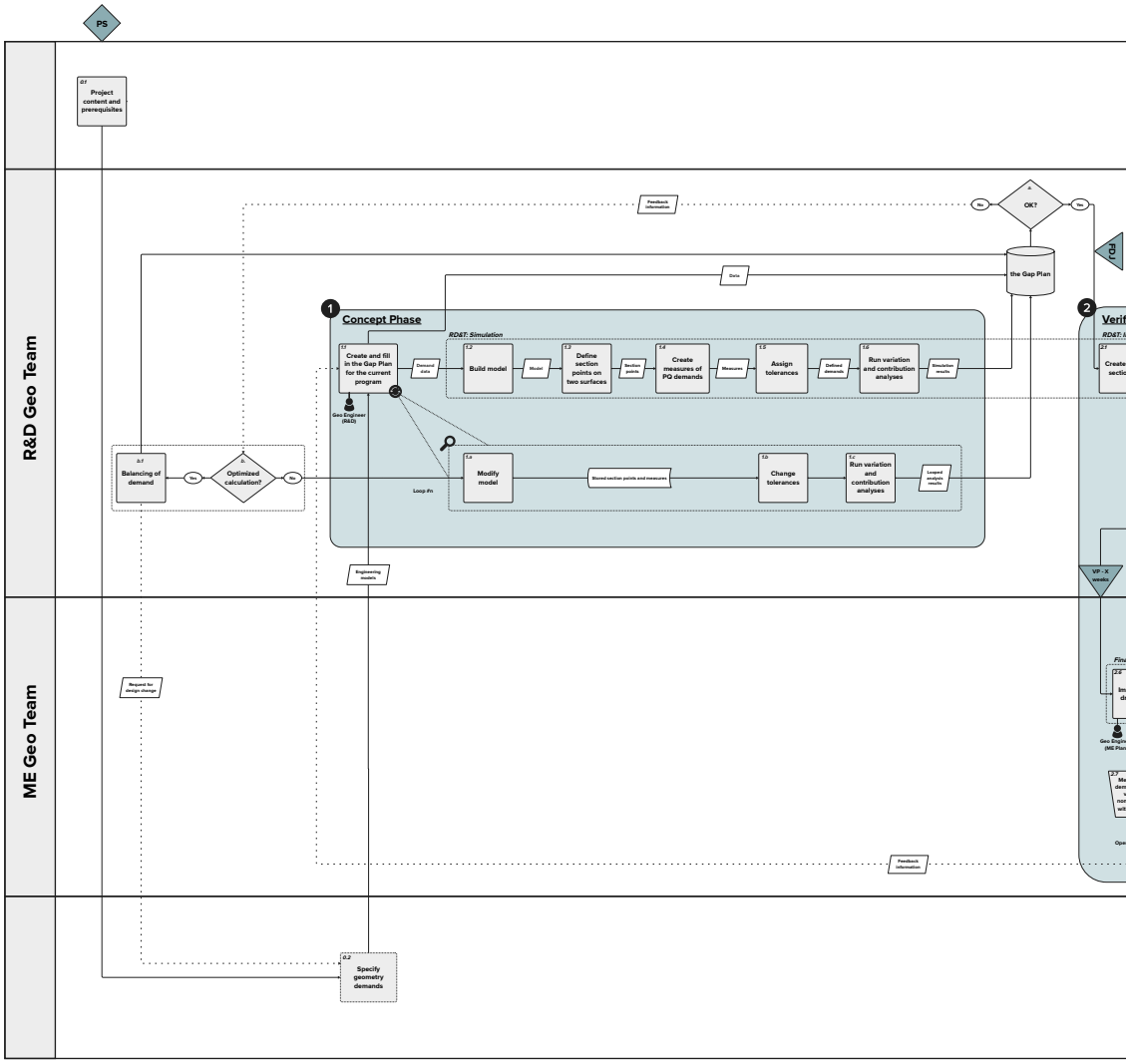

Figure 4.4: Initial segment of the flow diagram.

As depicted in the first segment of the flow diagram, as seen above, the initial step occurs at PS, where the project content and prerequisites are established. Since this step is crucial before commencing the actual process, it was considered necessary to include it. The flow then progresses to the design and engineering team within the R&D department, where the geometry demands are specified before transmitting the demand data to the R&D Geo team.

The Concept Phase numbered as *1* in the figure above, commences with the creation of the Gap Plan in Excel, which is completed by the Geo Engineer from R&D. Subsequently, the Geo Engineer progresses to the simulation, utilizing RD&T, where the input data consists of demand names and types extracted from the Gap Plan and relevant CAD files. The software process initiates by constructing the simulation model, which also serves as the output data, followed by defining section points between the surfaces to facilitate subsequent measurements. This section point data is then utilized to generate measures of PQ demands, such as gap and flush. Following this, tolerances are assigned, resulting in finalized simulation models. This enables

the execution of various analyses within the software. The output comprises the analysis results, which are then manually entered into the Gap Plan to determine if the demand aligns with the target value for proceeding to the next phase. This evaluation is visually depicted in the Gap Plan, where green signifies compliance with the demand and red denotes that it failed to meet the demand, providing the necessary information to address decision point *a* in the flow diagram.

In the case of the demand being indicated as red, meaning it does not comply with specified demand data in the Gap Plan, the information is looped back to a decision point. Here, the calculation undergoes evaluation to determine if it has been adequately optimized. If the answer is affirmative, the demand is balanced. This involves adjusting the demand or altering the design using various methods, dependent upon the desired outcome. Subsequently, the output data flows back into the Gap Plan. In cases where the design is modified, resulting in a less sensitive demand, the calculation yields an affirmative result. Another approach to design modification involves identifying the demand as unnecessary and removing it. For instance, this could entail eliminating a demand. However, if the answer is negative, indicating that optimization is not sufficient, the simulation undergoes looping, as illustrated in the zoomed-in section of the figure above. The looping process may occur multiple times until the result is deemed satisfactory or accepted without further modification. The looped simulation begins with the modification of the model to optimize the results. The section points and measures generated in the initial loop are stored within the software and reused in subsequent iterations. Subsequently, the process moves to adjusting tolerances, followed by another round of analyses. The results of these looped analyses are then integrated into the Gap Plan to reassess compliance with the requirements.If the changed results are satisfactory, the flow proceeds to the Verification Phase. This phase often occurs immediately after the FDJ is established, coinciding with the ordering of the nominal buck.

The Verification Phase is commenced by conducting the inspection preparation in RD&T, using the same session and performed by the same Geo Engineer from R&D Geo team, as depicted in Figure 4.5.

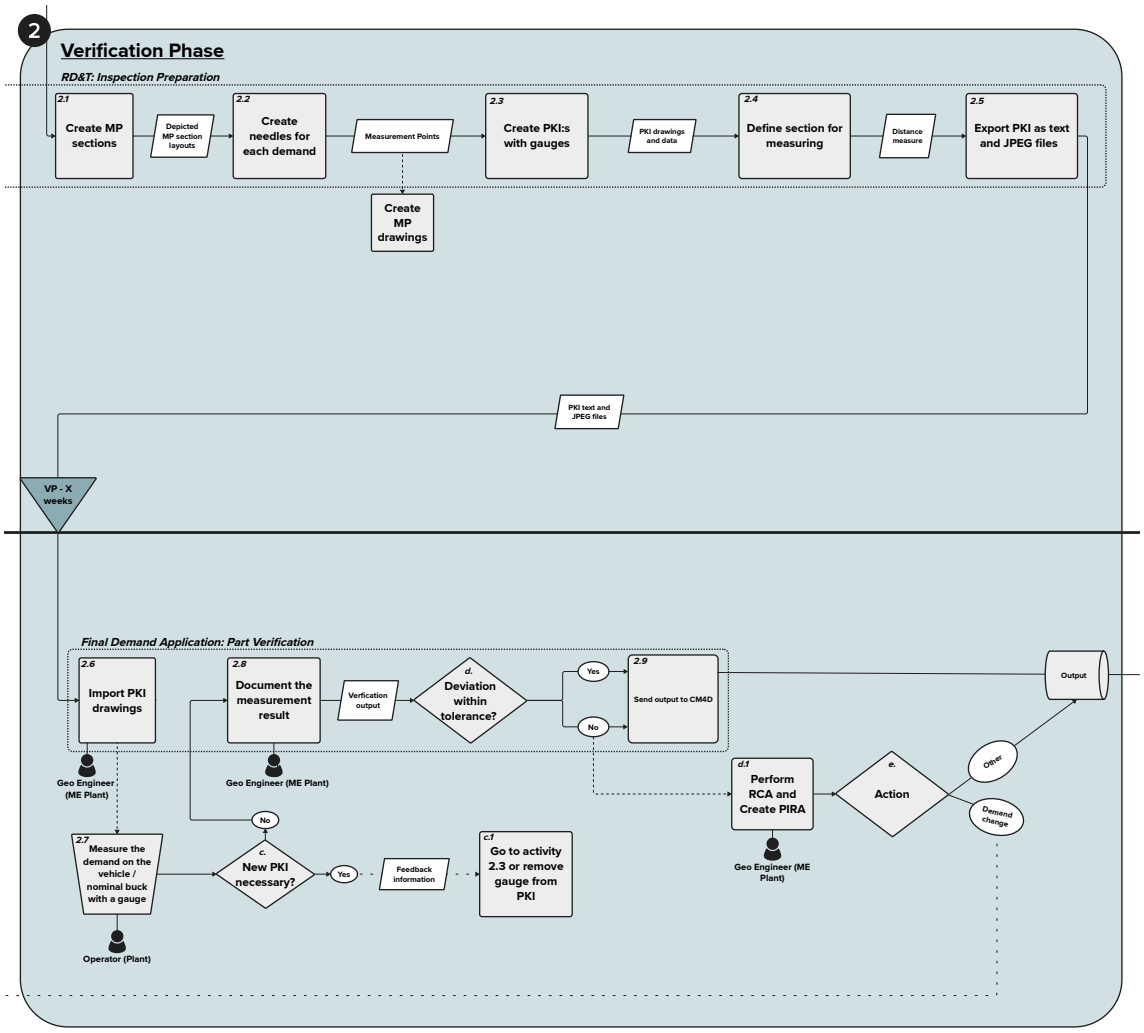

Figure 4.5: The Verification Phase in the flow diagram.

The ongoing process in RD&T is followed by the creation of MP sections, resulting in the output of MP section layouts. This data is subsequently utilized to generate needles to create measurement points for each demand found in the Gap Plan, which the Geo Engineer is currently working on. In parallel to the main work flow, the output of measurement points may also be employed to generate MP drawings if necessary. The output data, comprising measurement points, is then employed to create PKI:s using Polestar's gauges. The digital gauges represent the physical gauges utilized in the plant for the part verification. This results in the generation of PKI drawings and associated data. All data from preceding activities is then utilized to export the PKI:s as text and JPEG files. That output can then be shared via SharePoint, or sent via email if needed to the next Geo Engineer, who is a part of the ME Geo team working at the plant.

Between the last activity in RD&T and the part verification in FDA, there is a stage labeled as "VP - X weeks." This signifies that it occurs a few weeks before the construction of the VP begins. Until this point, any necessary changes to the PKIs can be made. Otherwise, the engineers will wait for the construction to com-

mence. Subsequently, the Geo Engineer from the plant initiates the necessary work in FDA. The PKI data provided by the Geo Engineer from the R&D Geo team is manually imported into FDA. To progress within the application, an operator at the plant measures the demand on either the vehicle or nominal buck, using a gauge. At this point, it becomes apparent whether the measurement method and instruction can be used. This evaluation determines if there is a need for a new PKI, which is assessed by the Geo Engineer. If there is a requirement for a new PKI, the information is utilized to revise the existing PKI in RD&T. Conversely, if there is no need for a new PKI, the operator's measurement results from a vehicle are manually inputted into FDA by the Geo Engineer for documentation. This process yields the verification output, which is then assessed in the software to determine if it falls within acceptable deviation limits. Similar to previous steps, this assessment is also represented by green and red indicators, with green indicating an accepted result and red a rejected result. All verification outputs are directed to the activity of sending the output to CM4D within the application. However, if the result is marked as red in the FDA, a parallel flow is initiated. To assess the cause of the problem, an RCA is performed, followed by the creation of a PIRA. The output of this process then leads to taking some form of action. If a demand change is deemed necessary, the information is fed back to the R&D Geo team and their Gap Plan. Conversely, if any other action is required, the output is directly sent to CM4D, which is automatically done by FDA.

As the output is sent to CM4D, the Production Phase is automatically initiated, comprising the third phase in the process flow diagram, as illustrated in Figure 4.6 below. The scope of the study does not proceed further than this point, marking the termination of the analyzed data flow.

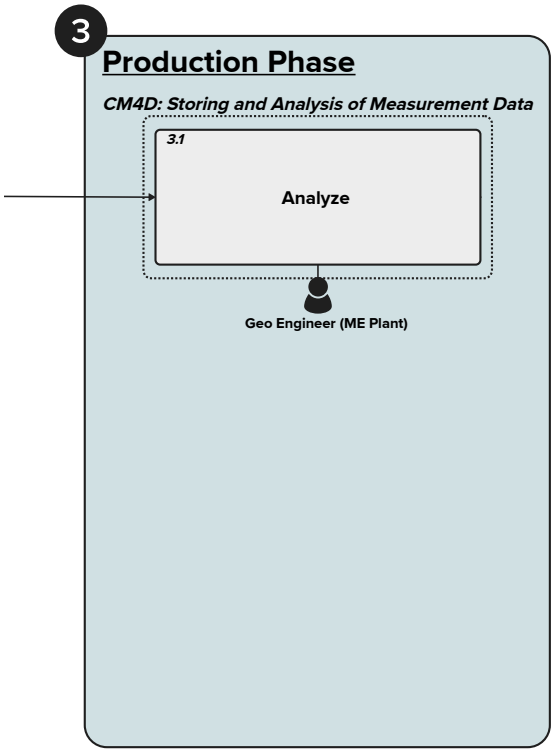

Figure 4.6: The Production Phase in the flow diagram.

4.1.4.2 SIPOC Diagram

An overview of the process flow can be seen as a SIPOC diagram in Figure 4.7. The respective departments involved in the process are listed as *suppliers* of the inputs and *customers*, meaning receivers, of the outputs from the process. A brief overview of the workflow with the key steps is seen in the process column in the diagram, aligned with the corresponding inputs and outputs linked to their respective suppliers and customers.

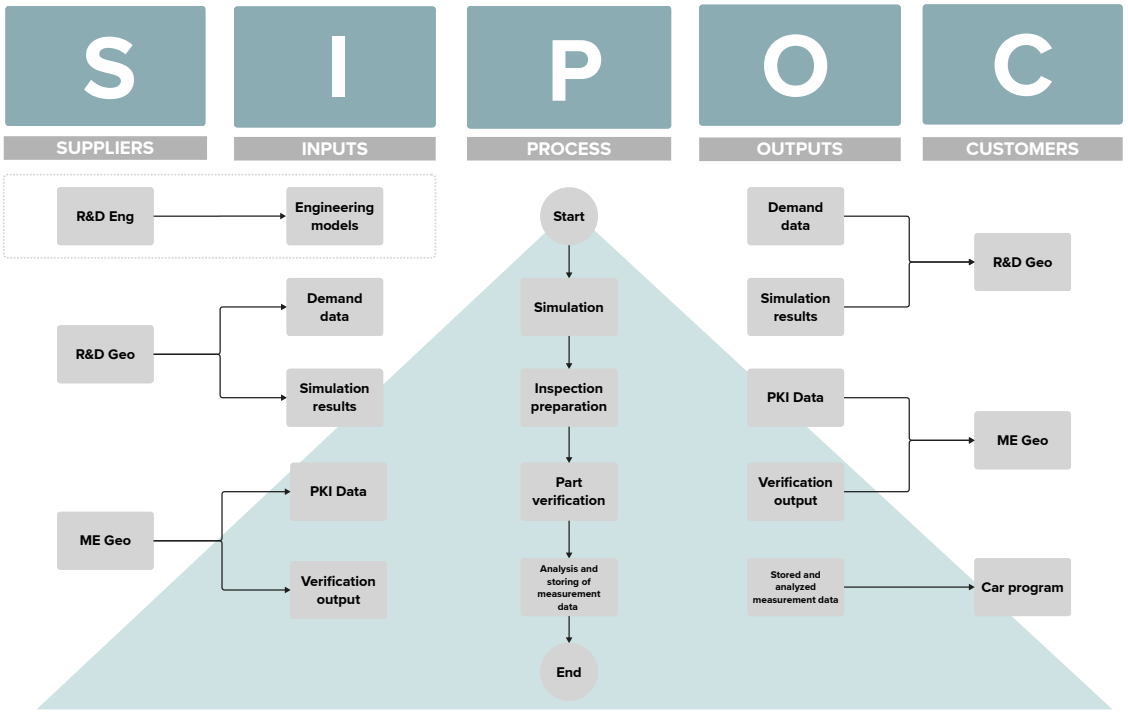

Figure 4.7: SIPOC diagram.

R&D Engineering, *R&D Eng*, is included as a supplier in the diagram, as they provide the R&D Geo team with the input *Engineering models*. As their role is not included in the scope of the process that is studied, their work is separated with a dashed border. Further, *Car program*, which is the entire development project of the final product, is placed as the customer for the final output of the process.

4.1.5 Pilot Process

This subsection presents the results of conducting the Pilot Study of the current process in three phases: Concept, Verification and Production.

4.1.5.1 Concept Phase

The two selected demands, along with their corresponding components, were EX076 and EX077, which included the components “Rear Fender” and “Rear Body Lamp”, placed in the backside of the vehicle. Both demands include gap and flush requirements with imaginary values, as there are split-lines between them that require measurement and tolerances. The demands can be seen in Figure 4.8, adapted from the Gap Plan.

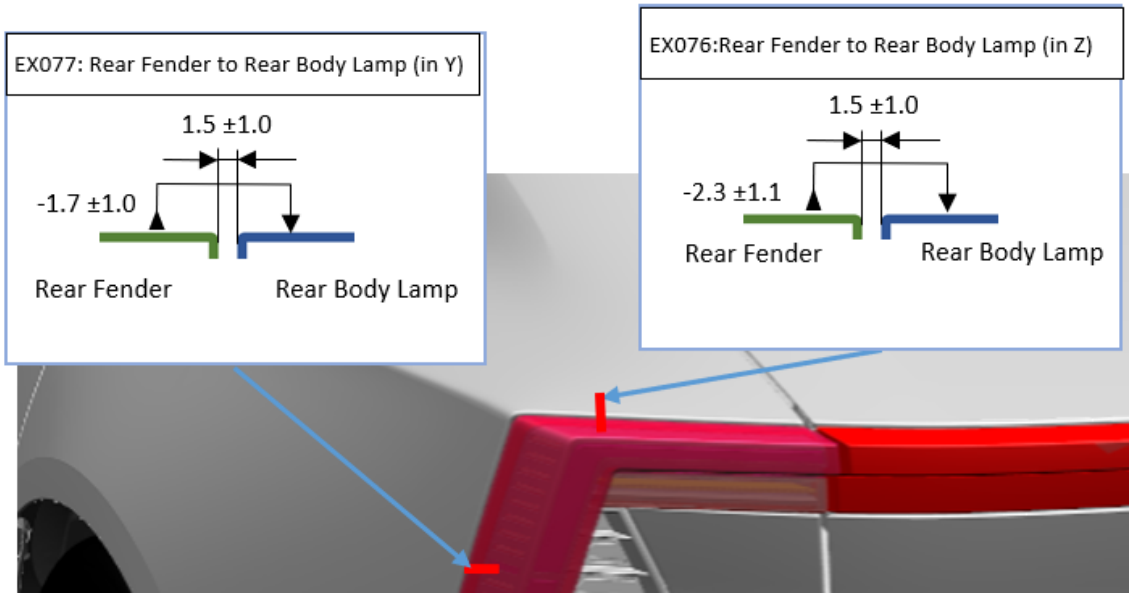

Figure 4.8: Visual representation of the placement of demands EX076 and EX077 with imaginary values.

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As seen in the figure above, the demands exhibit both a nominal value and a tolerance for both the gap and flush requirements, as detailed in Table 4.1 below.

Table 4.1: Demands EX076 and EX077.

Demand name	**EX076**		**EX077**	
Type of requirement	Gap requirement	Flush requirement	Gap requirement	Flush requirement
Nominal target value	1.5	-2.3	1.5	-1.7
Tolerance	+/- 1.0	+/- 1.1	+/- 1.0	+/- 1.0
Direction	Z	Z	Y	Y

The chosen components and demands put into RD&T yielded the following results of the measurements shown in Figure 4.9.

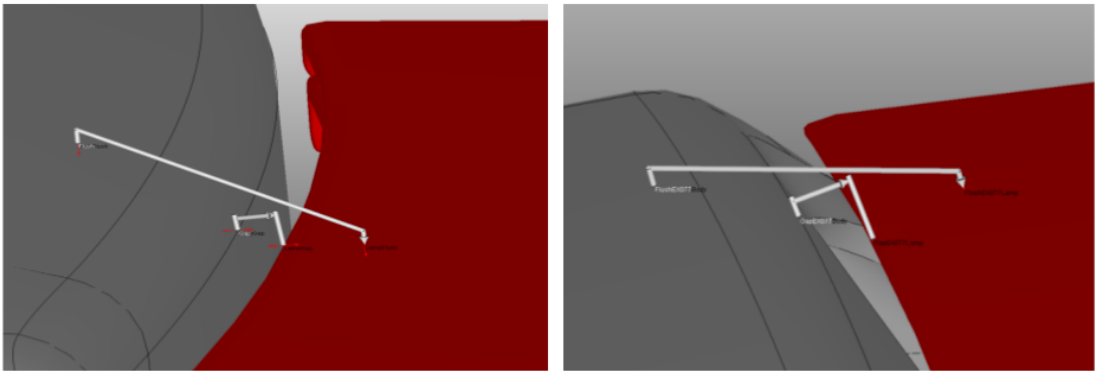

Figure 4.9: The gap and flush demands as measures in RD&T (EX076 to the left and EX077 to the right).

The figure illustrates that the measurement of the gap demand is taken at the outermost corner of the curved edges of the components, while the flush demand is measured from the visible Class A surfaces. Further, the measurements, along with the assigned tolerances from the tolerance chain in the components, produced the results of the variation analyses for the gap demands, shown in Figures 4.10 and 4.11.

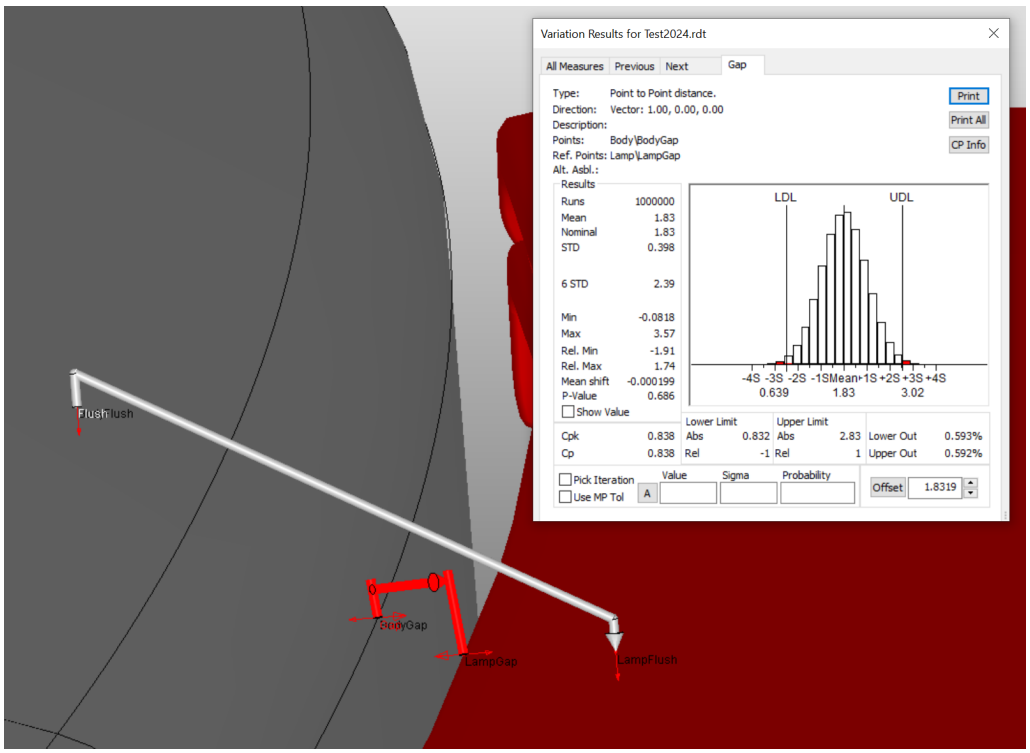

Figure 4.10: Variation analysis results from RD&T for EX076 (Gap demand).

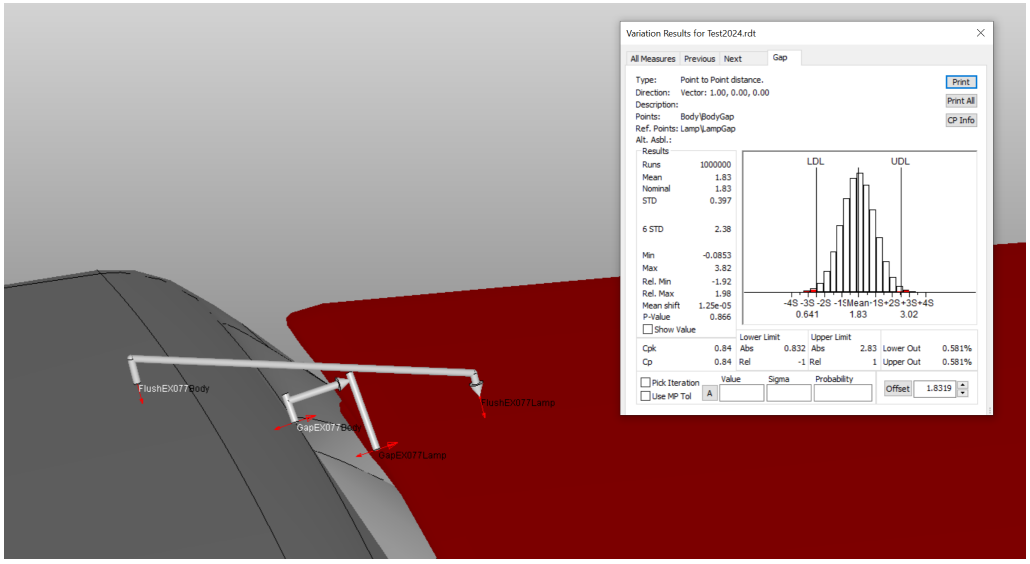

Figure 4.11: Variation analysis results from RD&T for EX077 (Gap demand).

Similarly, the variation analysis was conducted for the flush demand and that yielded the results presented in Figures 4.12 and 4.13 below.

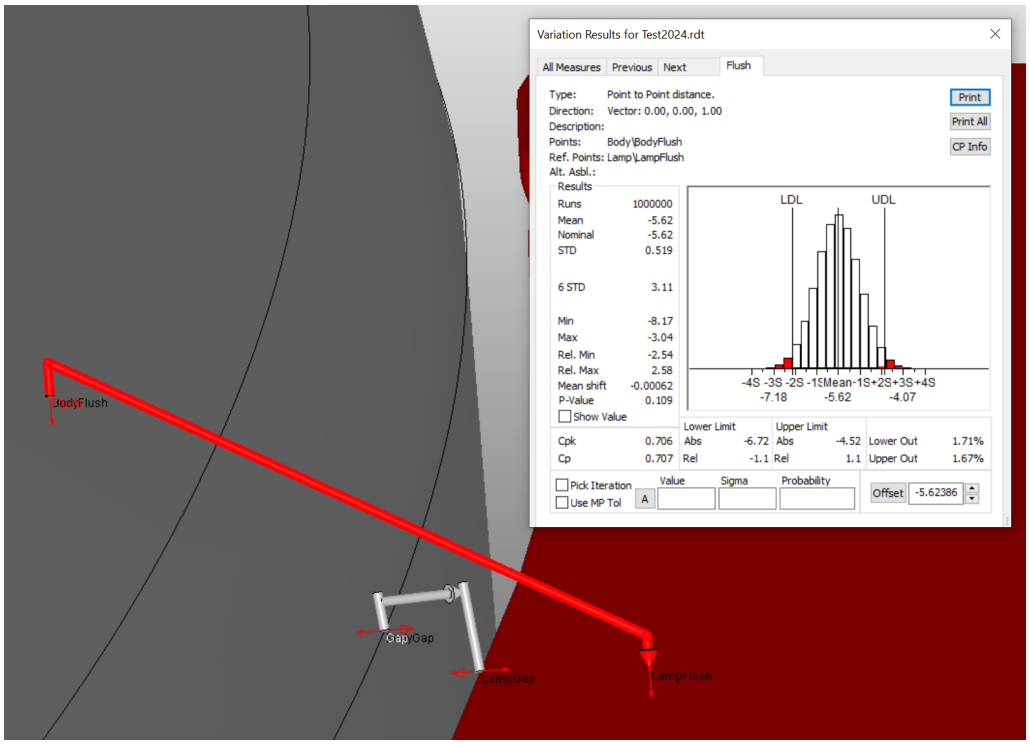

Figure 4.12: Variation analysis results from RD&T for EX076 (Flush demand).

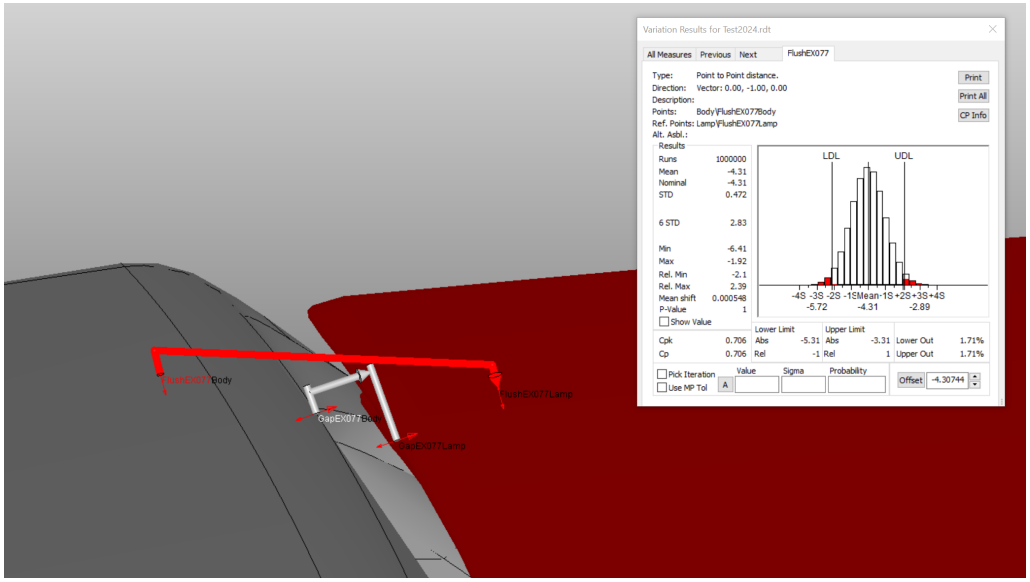

Figure 4.13: Variation analysis results from RD&T for EX077 (Flush demand).

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The final results were compiled in an RD&T-based document, which can be seen in Figures 4.14 and 4.15. These results were controlled by comparing them with the values in the Gap Plan.

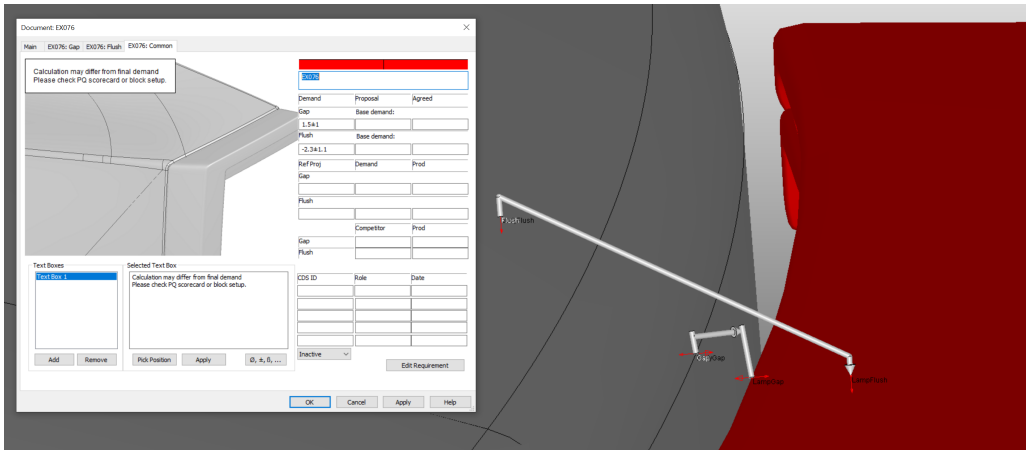

Figure 4.14: Results for demand EX076.

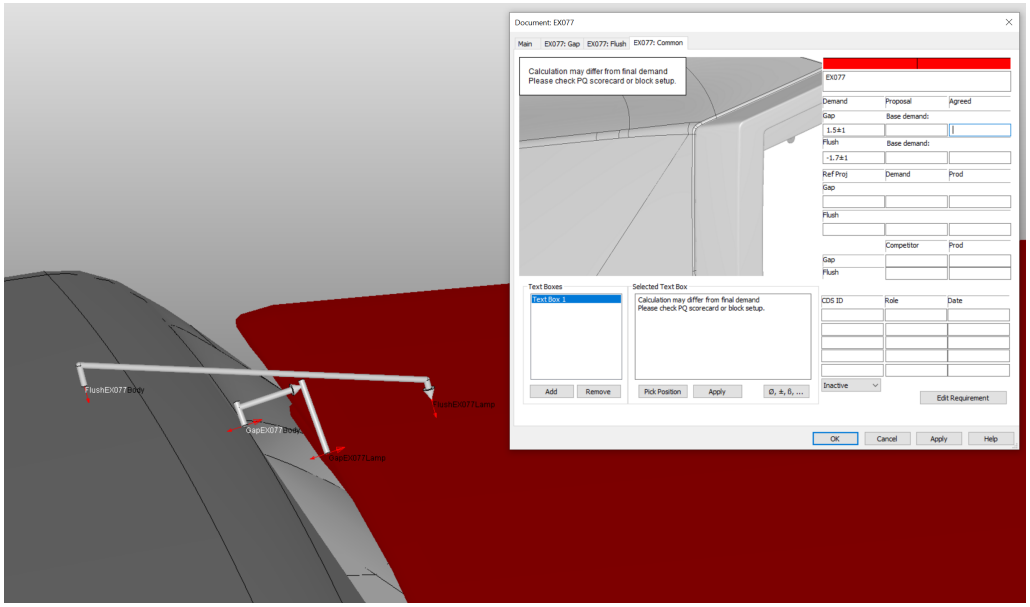

Figure 4.15: Results for demand EX077.

As the results, seen above, were not affirmative the values were compared with the target values in the Gap Plan to see if it was within acceptable tolerance or not. With help from experts, the demands were accepted to proceed to the next step. If it were not accepted, it would have needed a balancing of the demand or design.

4.1.5.2 Verification and Production Phase

The needles creating measurement points can be observed in the MP sections. In Figure 4.16, the MP section for demand EX076 is depicted, which looks the same as the MP section for demand EX077. It visualizes the cross section that shows the relation between the components.

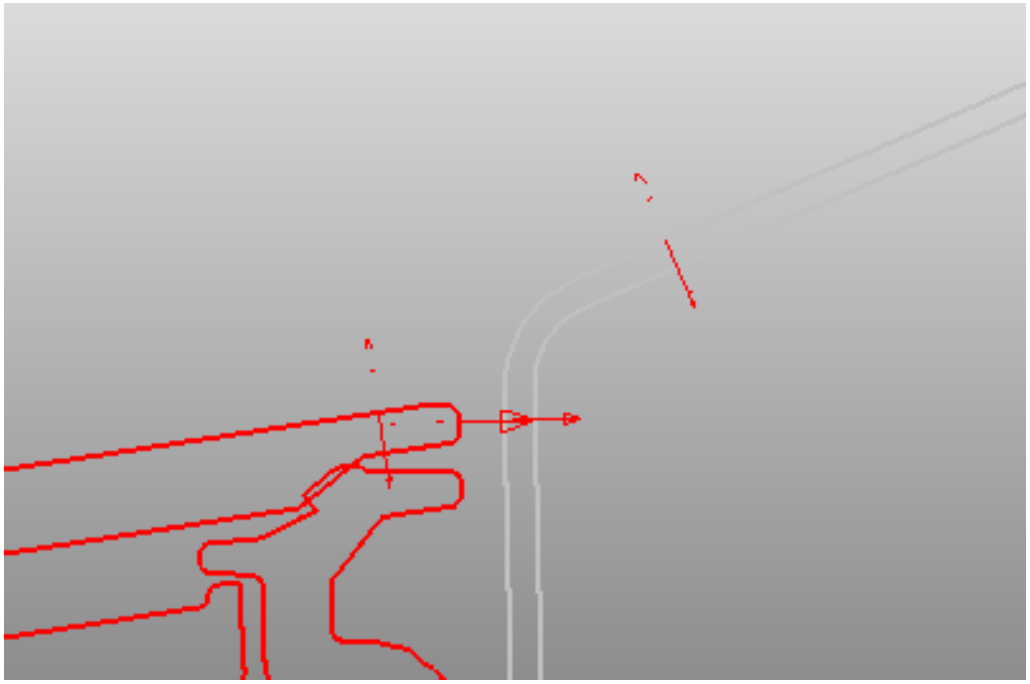

Figure 4.16: MP section for demand EX076.

In Figures 4.17 and 4.18, the MP drawings can be found where the placement of the demands is visible on the components.

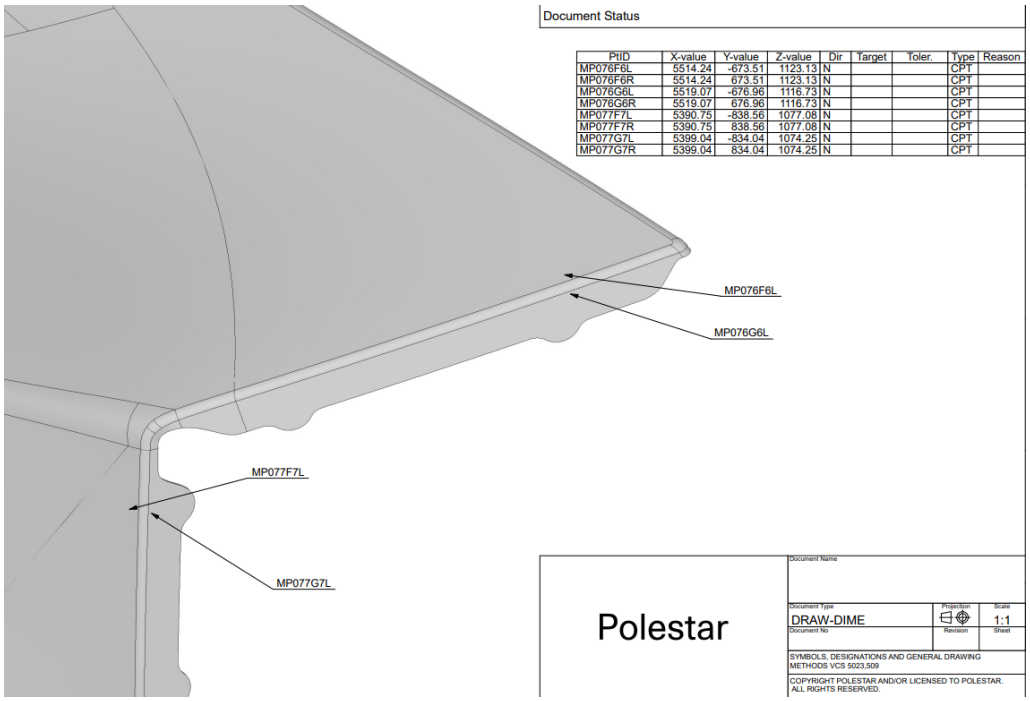

Figure 4.17: MP drawing for the rear fender.

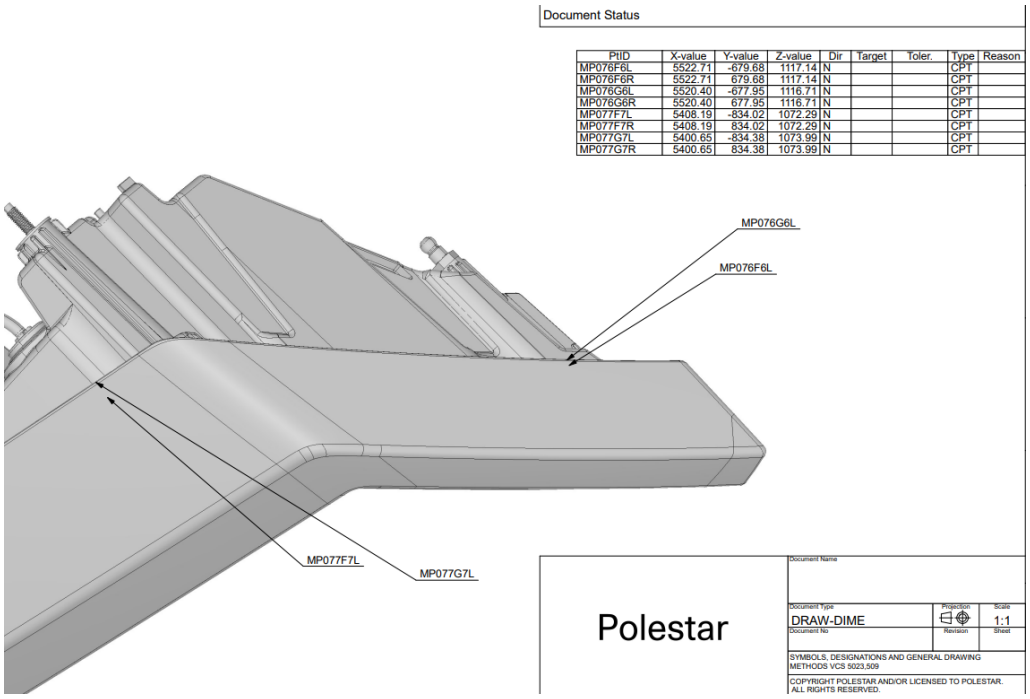

Figure 4.18: MP drawing for the rear body lamp.

PKI drawings were created in the MP sections for the EX076 gap and flush demands, which can be found in Figures 4.19 and 4.20. The gauges measuring the relations are visualized in the drawings, with the measured values presented in the table below the pictures.

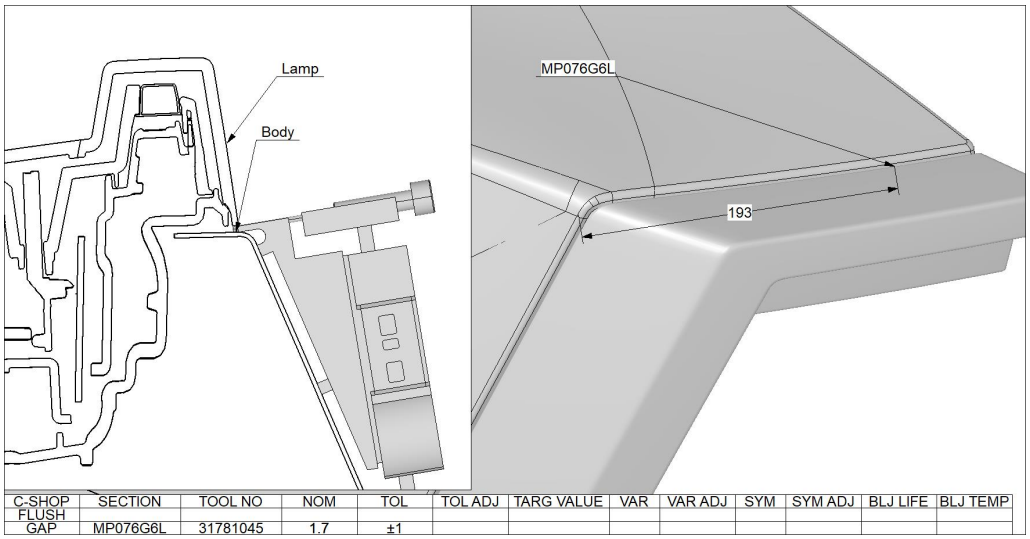

Figure 4.19: PKI drawing with gauge for EX076 gap demand.

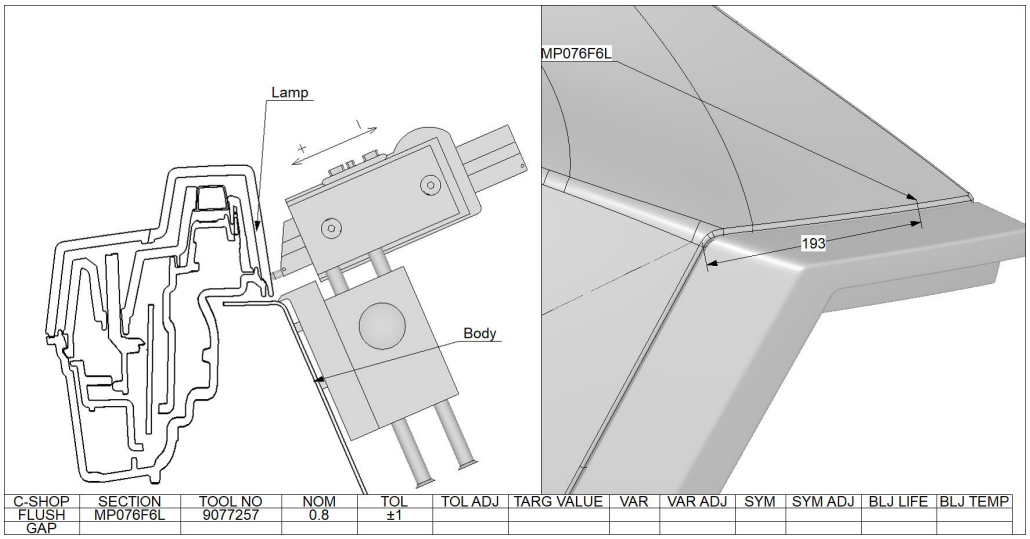

Figure 4.20: PKI drawing with gauge for EX076 flush demand.

The PKI drawing imported into FDA prompts the application and several inputs are chosen to proceed. *Site* and *project* were assigned. Once the inputs were assigned the button "Measure" was clicked to prompt the "Measurement" page, which can be seen in Figure 4.21.

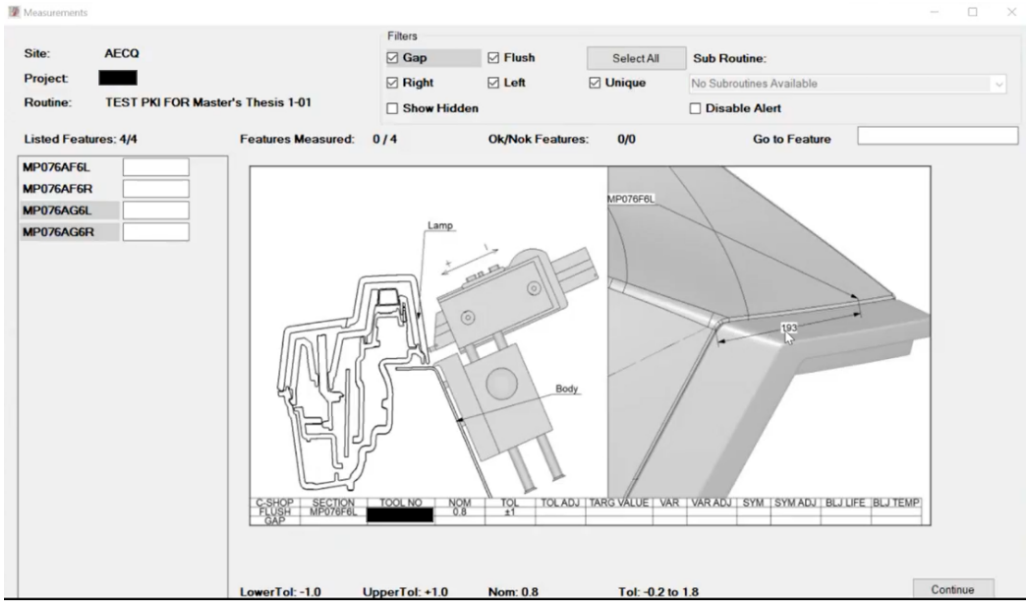

Figure 4.21: Measurement page in FDA.

The imported PKI drawings are shown in the figure above as features, where the drawing changes as the measurements are filled in. Parallelly, the results from the operator measuring the nominal buck with the assigned gauges were conducted and the documented result can be seen in Figure 4.22.

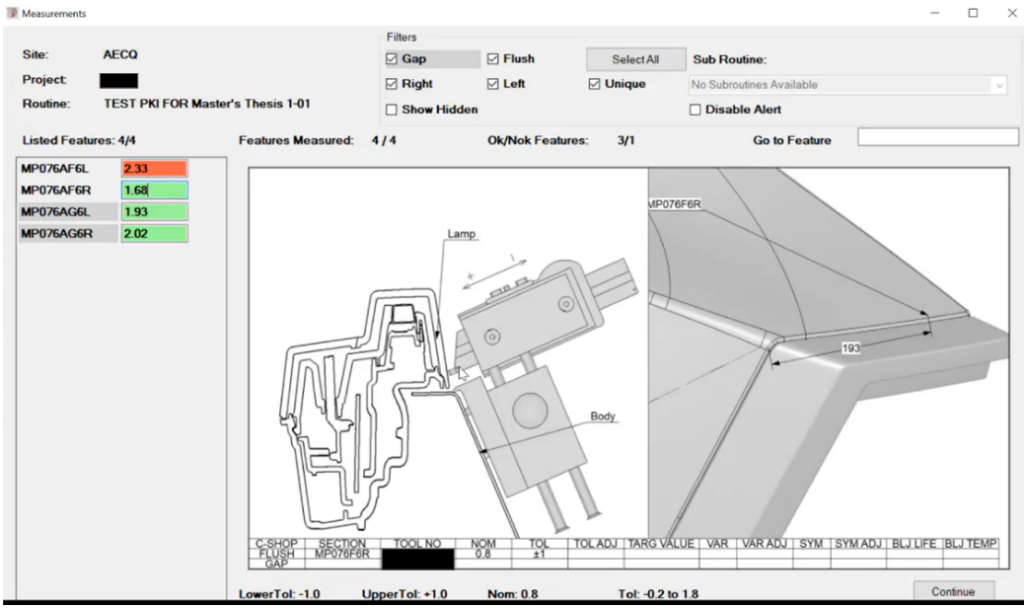

Figure 4.22: Results of measurements on the nominal buck.

In the figure above, it can be seen that three out of four demands are marked as green, while the fourth one is marked red. Next, the results are filtered according to the input boxes, such as *Body ID*, *Measurement Type* and *Build Series*, which can be seen in Figure 4.23.

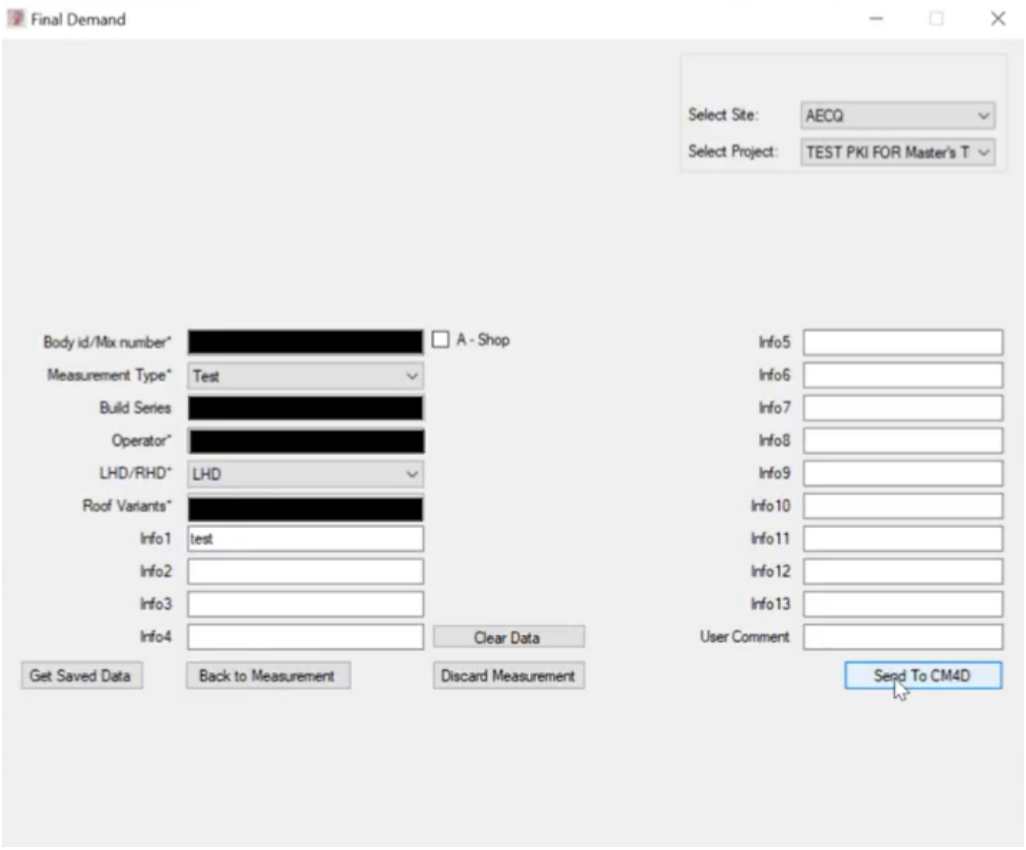

Figure 4.23: Filtering of the measurement results.

The results sent into CM4D are graphically visualized to show the correlation between the final demands and components, which is depicted in Figure 4.24.

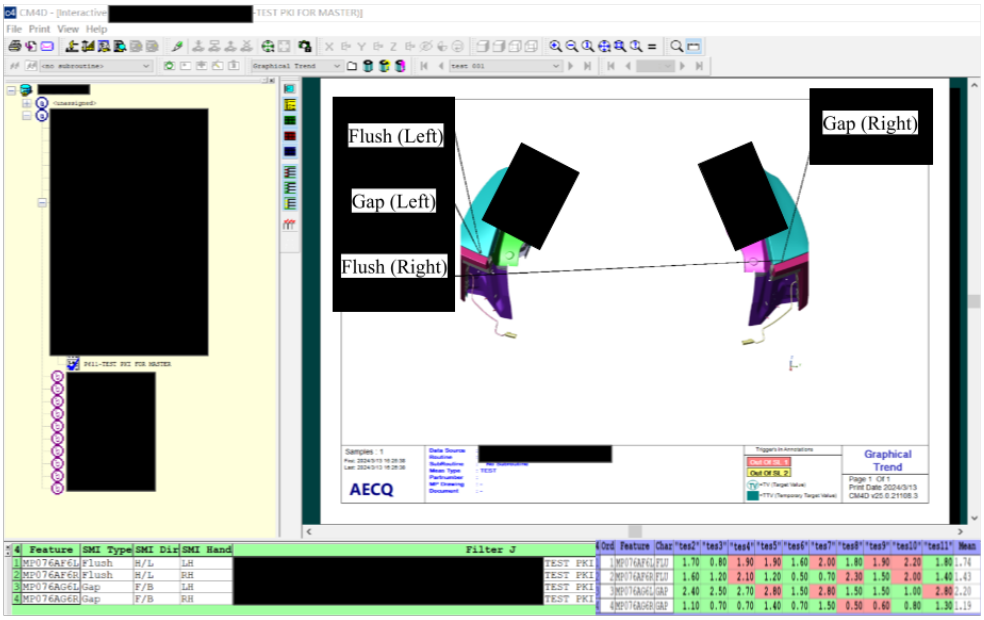

Figure 4.24: The results in CM4D where the confidential information is covered.

In the figure above, the graphical representation of the final demands can be observed, as well as the iterated measurement results in the lower right corner. Additionally, the user can ascertain whether it is fulfilled and review the imported numerical results measured by the FDA.

4.2 Facets of the Current Process

The facets of the current process are addressed in this section, where the findings derived from in-house interviews and the Pilot Study will be presented to provide a comprehensive understanding of the various aspects of the current process.

4.2.1 Interviews within Polestar

In this subsection, the facets of the current process derived from interviews conducted with engineers within the organization are presented. This includes the most apparent challenges, potential consequences of those challenges, strengths, improvements, and lastly, a summary of those findings. The transcription of the interviews can be found in Appendix D

Challenges
Firstly, the content analysis resulted in several findings of similarities in the answers given regarding challenges with the current process. The time perspective was found to be the most significant challenge, where several respondents claim that the pro-

cess lacks a proper time plan including deadlines for deliverables. Further, some respondents experience a lack of a standardized work process with clear instructions and a common understanding of the work. Thus, some of the respondents claim that they have established an individual-based working procedure, due to lack of instructions. It was also mentioned that there is not always a clear, common agreement on the work among the teams, as official hand-shakes between the teams are missing in some cases. Additionally, the storing and hand-overs of data were described as unstructured, specifically in the Concept Phase. This is believed to be a consequence of manual data management in some activities, which was also indicated to be a common challenge among the respondents.

Another challenge emphasized particularly in the Concept Phase, is the absence of a department that specializes in PQ at Polestar. The respondents engaged in the Concept Phase explained that PQ is informally integrated into their process, as there is a collective responsibility within the team. The R&D Geo team involved in the Concept Phase is expected to consider PQ when conducting their work, relying on their personal experience and expertise although none of them are PQ experts. Furthermore, one of the respondents from the Concept Phase emphasized that their team primarily focuses on dimensional engineering and lacks the perspective of PQ engineers. PQ engineers not only consider dimensional appearance but also conduct thorough historical research and market benchmarking. Consequently, the absence of in-depth work from a dedicated PQ department, as highlighted by both respondents from the Concept Phase, may interfere with the holistic view of the vehicle's appearance.

It was also emphasized that it is challenging to ensure that other teams understand the data, particularly from the R&D Geo team in the Concept Phase, which ends up with irrelevant analyses made by other teams.

Potential Consequences of the Challenges

The respondents claim that as a result of the above mentioned challenges, the process can become time-consuming which can cause delays. As the process appears unstructured, it leads to difficulties with navigating through the work process and tracking the data flow. Other consequences include sensitivity to variation and deviation. Most respondents claimed that as a result of the absence of a defined, standardized work process, a lot of the work conducted by the engineers has become individual-based. Thus, deviation factors such as a personnel change would imply a significant challenge in the work process. Additionally, one respondent explained that this highlights the necessity for proper gateways, as agreements were often based on trust. Without such formal checkpoints, potential challenges, as implied by the respondent, may arise in reality. This could lead engineers to proceed with activities even though prior tasks have not been completed or approved. Finally, unspecified collective responsibility, like in the case of PQ, can cause issues with a lack of responsibility.

Strengths

The most commonly mentioned strength of the process is that the communication works well, although it is not entirely formal since it is carried out through mail conversations without following a set standard. Another strength mentioned by the respondents is the fact that eventually, the work gets done, although it is not done through a well-defined process. The quality of the work relies highly on the expertise of the engineers, meaning that they manage to obtain good results even without clear instructions. This demonstrates a strength within Polestar as an organization, as it enables agile and rapid decision-making processes.

Improvements
Among the suggestions on how the process can be improved and managed more efficiently with regards to data management is firstly a more evident time plan, including clear deadlines and deliverables. Further, more efficient hand-overs and official hand-shakes between the teams are necessary, along with options to track and store data. Another improvement is establishing a collective agreement on the work process, which can be obtained by clear instructions and objectives. This includes an evident process for iteration and feedback between teams. Finally, smart solutions such as automated management of data transfer and formatting between steps in the process would enable it to be more structured. As one respondent said:

"*The culture at Polestar is not used to standards but it needs a change...a standardized process is needed with room for own initiative*"

The quotation suggests that the organization requires a standardized process that is sufficiently detailed to allow for individual initiative without hindering creativity.

Summary
The key takeaways from the analysis highlighting significant reoccurring findings from the interviews are summarized in Table 4.2.

Table 4.2: Key takeaways from analysis of interview answers.

Key questions	Common findings
What are the most commonly mentioned challenges with the process?	• Time management and deadlines • Absence of PQ department • No proper deliveries • Lack of standardized work process • Lack of common understanding and agreement • Lack of official hand shakes • Manual handling of data • Lack of proper hand overs • Unstructured storing of data (in concept phase)
What are the most commonly mentioned strengths of the process?	• Communication works well (but it is informal) • The work gets done (but not by a well defined process)
How can the process be improved and managed more efficiently?	• Automated data management and formatting • Well defined deadlines and deliveries • Evident process for feedback and iteration • More efficient storing and trackability of data • Official agreements on the work process

4.2.2 Findings from the Pilot Study

The identified bottlenecks and ineffective methods encountered during the Pilot Study can be found in Table 4.3. The findings are categorized based on the corresponding activity or document that was found to have bottlenecks.

Table 4.3: Identified bottlenecks from the Pilot Study.

Area of improvement	Identified bottleneck/ineffective method(s)
1. The Gap Plan	1. Manual input to the Gap Plan from demand data* 2. Manual input from RD&T 3. Unstructured Gap Plan a. Demands not linked between list and sheets in the Gap Plan b. Having to click around through many demands 4. Manual update of changes 5. Not linked to other databases a. RD&T 6. Anyone can modify
2. RD&T: Simulation	1. Looping several times a. Manually changing values several times 2. Manual check 3. No standardized process for tolerancing 4. Manual output to the Gap Plan to see if it is green/red → time-consuming when handling a lot of demands at the same time
3. RD&T: Inspection preparation	1. Manual input from the Gap Plan 2. Finding a suitable gauge 3. Have to update PKI JPEGs if something needs to be changed manually a. Export manually each time to FDA (not linked)
4. FDA Part verification	1. Manual input of PKI data 2. Manual input of verification results to FDA 3. Calibration of gauge*
5. Feedback / iteration	1. No standardized process for feedback (in general)

In the table, findings coded with a star sign (*) indicate that they fall outside the scope of this report. For instance, the issue with calibrating the gauges numbered 4.3 requires precision from the engineer and cannot be solved in any other way, unless changes are made to the construction of the gauge. This is not within the focus area of the thesis as it concerns the manufacturer of the gauges and does not directly relate to the process and data flow at Polestar. Similarly, the manual input to the Gap Plan from the demand data numbered 1.1, relates to a department that provides the demand data before the process commences, which is why that step is recognized but not within the scope.

Furthermore, findings numbered in the table without a star sign (*) are those that will be processed and evaluated for improvement.

4.3 Facets of Processes at Competing Companies

The interviewed engineers, outside the company, were the following:

- Principal Engineer at the department of PQ at Volvo Car Corporation, *VCC*, in Gothenburg, Sweden.

- Head of Project Quality and Vehicle Integration at ZEEKR (former CEVT) in Gothenburg, Sweden.

The conducted interviews lasted approximately one hour each and the transcribed answers for each participant can be found in Appendix G.

The content analysis of the answers revealed more similarities than differences, despite the interviewees being from different companies. The key findings gathered from the interviews are presented below.

Challenges
The challenges identified in their GA processes, consistent for both companies, include the need to balance technical attributes, such as safety requirements, with PQ attributes. This necessity leads to compromises between the two during the vehicle development process. The interviewee from VCC mentioned that they constantly hold meetings to discuss the overall perception the car needs to give to its customers, making trade-offs accordingly. Similarly, the interviewee from ZEEKR mentioned iterative meetings with other departments to assess trade-offs, all stemming from the core feeling and perception the car and brand aim to convey. This was conveyed as a challenge, as the PQ departments are often not the ones making the final decision. Consequently, the PQ suffers, impacting the overall GA.

Furthermore, the competing companies, being larger and more established, encounter difficulties in making changes later in the process. This challenge arises due to clearer delivery times and defined points when the design is closed for changes. Additionally, because of their size, these companies have production facilities in different countries, leading to various suppliers and, consequently, variations in meeting requirements. This diversity imposes a challenge in identifying patterns of the problem, as finding the root cause becomes more challenging.

Strengths
The competing companies, each with a dedicated PQ department, exhibited several strengths. The primary advantage, as highlighted by both interviewees, was that involving a PQ department in the product realization loop. Consequently, it provided a more comprehensive view of the vehicle in the GA process. This holistic approach enhances attention to detail across the entire car, which can be more challenging without a clear PQ directive. Additionally, having a PQ department was noted to elevate the overall quality of the car, giving it a more premium feeling. The interviewee from ZEEKR shared an example from the company's history when they did not have a PQ department, resulting in a car with a significantly lower premium feeling. This experience underscored the importance of incorporating a PQ perspective in their processes.

Furthermore, both interviewees mention that their companies manage demand data using a common digital platform within their organization, making it well-documented and traceable, which is considered valuable for the process. This approach enhances

the feedback and iteration process, as everything is well-documented. The effectiveness of the feedback and iteration process also depends on the companies having well-defined gates and check-ins during their product developments, ensuring that everyone knows what they need to do and when to deliver their tasks.

Improvements
Although well-documented requirements data is considered a strength, both interviewees implied that the actual data management and manual inputs from their software to their digital platforms consume a significant amount of time, an aspect they would eagerly improve in the future. The most prominent suggestion for improvement, as mentioned by the interviewees, would be to automate the data inputs to save time and allocate it to other parts of the process, thereby enhancing efficiency. Another improvement highlighted is the importance of maintaining cohesion within the PQ department, emphasizing the need for a holistic approach at all times.

Summary
Table 4.4 summarizes the advantages of having a PQ department, challenges, strengths and improvements mentioned by the participants.

Table 4.4: Key takeaways from analysis of interview answers with engineers from competing companies.

Key questions	Common findings
What advantages does a PQ department give to a company?	• Greater holistic view of the vehicle • Better attention to detail • Improved quality of the car (premium quality)
What are the most commonly mentioned challenges with the process?	• Trade-off between PQ and other technical attributes • Changes late in the process • Requirement verification deviating on different sites
What are the most commonly mentioned strengths of the process?	• Well documented and traceable data • Well established feedback and iteration process • Well established gates and check-ins
How can the process be improved and managed more efficiently?	• Automated data management • Maintain an entirety within the PQ department

4.4 Solutions

This section encompasses the outcomes of generating solutions aimed at improving the data flow and overall performance of the process. The mapped areas for improvement are addressed, and the formulated solutions intended to tackle the challenges are presented.

4.4.1 Identified Improvement Areas

In this section, the focus areas for which the solutions were formulated are presented. The improvement areas are divided between data flow-related issues and process-related issues.

4.4.1.1 Data

Through the identification of bottlenecks and critical segments in the data flow, five main areas of concern were located in the flowchart. These areas are assessed to be in most need of a solution and are marked with red in the flowchart, as seen in Figure 4.25.

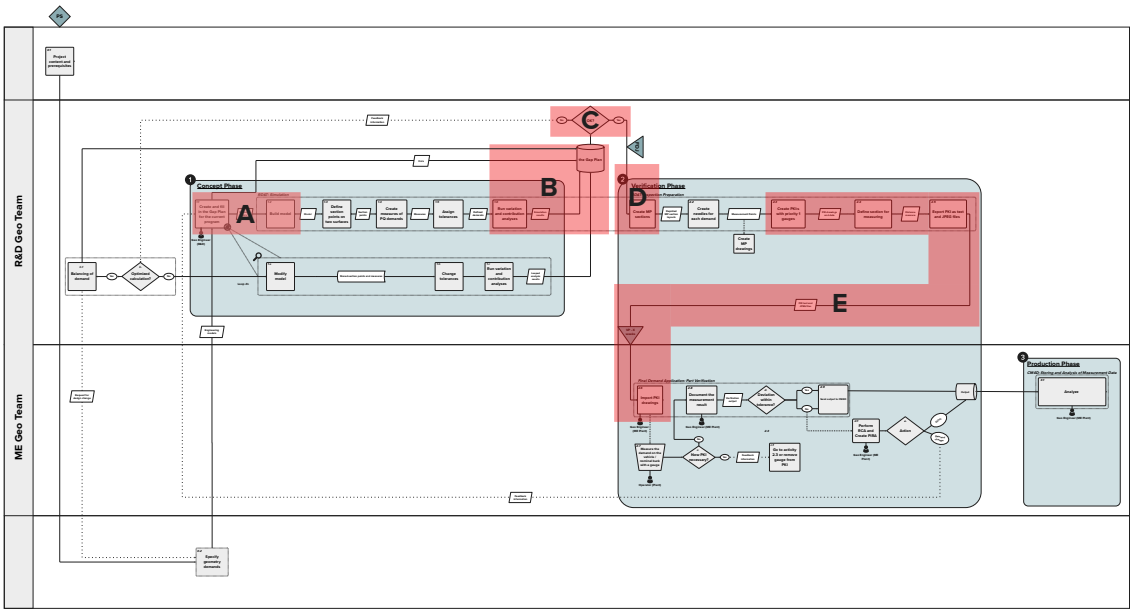

Figure 4.25: Identified Improvement Areas in the Data Flow.

The steps marked with red in the flowchart are the following:

- A (1.1 - 1.2): Implementation of demand data from Gap Plan to RD&T
- B (1.6 - Gap Plan): Implementation of simulation results from RD&T to Gap Plan
- C (a.): Sorting of green values (OK) from red values (NOK) in the Gap Plan
- D (1.6 - 2.1): Implementation of approved values from Gap Plan to RD&T
- E (2.3 - 2.6): Creation of PKI data files and export from RD&T to FDA

The above listed steps in the data flow are particularly critical because the data is converted between different softwares and requires reformatting. Currently, the data

is reformatted manually and entered manually into the following software, which is time-consuming and may impair the data quality significantly.

4.4.1.2 Process

The identified process-related improvement areas are compiled in the following list, numbered from 1 to 7 which further will be addressed.

1. *Time management and deadlines*
2. *Absence of PQ department*
3. *No proper deliveries*
4. *Lack of standardized work process*
5. *Lack of common understanding and agreement*
6. *Lack of official handshakes*
7. *Lack of proper hand-overs*

4.4.2 Formulated Solutions

The development of suitable solutions aimed at addressing the identified bottlenecks from Section 4.2 and improvement areas led to the creation of an API and supplementary process-related solutions. Two versions of the API have been formulated, including one semi-automated version and one fully automated version, where the latter is intended for future advancement. The rationale behind considering both versions is to present a feasible solution, achievable in the future with evolving technology, and in addition to that present another solution that explores future possibilities. As future technology remains beyond reach, the semi-automated version stands as the ultimate solution intended for this thesis, whereas the fully automated version is presented as a proposal for future advancement.

4.4.2.1 API

The proposed solution for addressing the critical segments within the complete data flow seen in Figure 4.25 in Section 4.4.1.1 involves implementing an API that enables the communication between the three softwares Excel, RD&T and FDA. The API facilitates the exchange of data in the correct format between the softwares and performs operations within the programs. This can be performed by incorporating standards for product data exchange, as described in Section 2.3.2. The data is exported from one software and converted into STEP AP242 or QIF 3.0 format depending on the capability of the software. Once the data is converted, the necessary information is extracted and reformatted to suit the following software. A session

is initiated within the program for each demand outlined in the Gap Plan.

The API consists of separate modules containing scripts that execute different operations. The first module addresses areas A, B, C and D in Figure 4.25, facilitating interaction between Excel and RD&T. Further, the second module addresses area E in Figure 4.25, enabling RD&T to communicate with FDA. There is an opportunity for manual intervention during program execution when it is necessary, and it is possible to switch between manual and automated operations by incorporating MBD. In some steps, engineer check-ins are necessary, and the scripts are programmed to await a manual prompt before proceeding with execution.

The full descriptions of the operations executed by the program in each module are given below, along with the corresponding inputs and outputs. For each module, a diagram visualizing the data flow and interaction between the softwares is presented, using the same symbol for the data as seen in Figure 4.3. The data symbol is colored to match the color of the symbol for the software program where the data is currently located. Further, the data passes through black boxes that represent scripts that execute the operations. The inputs and outputs of data from the black boxes are visualized without explicitly stating the operation being performed. Each black box is encoded according to which area in Figure 4.25 it addresses, indicating which step in the process described in Section 4.1.4.1 is executed.

Module ABCD: *Semi-automated version*
The first module addresses areas A, B, C and D. It is semi-automated, implying that it operates partially automatically and partly requires manual intervention. The operations within the module include the process across boxes 1.2-2.1, in the flow diagram seen in Appendix F. A diagram visualizing the data flow within the module, which is called module ABCD, is seen in Figure 4.26.

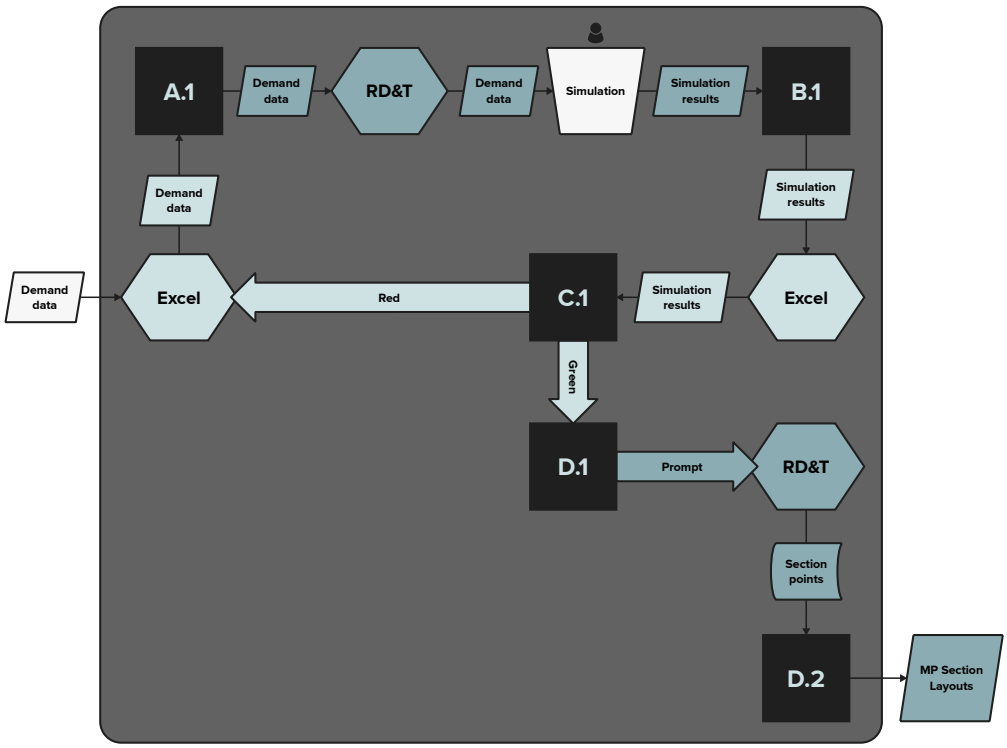

Figure 4.26: Semi-automated version of module ABCD.

The initial input to the module is data for a demand obtained from the engineering models that are entered into the Gap Plan in Excel. Thus, the data is initially located in Excel in the corresponding format, namely in the same color as the Excel symbol.

As the data enters black box A.1, the demand data is collected from Excel and reformatted utilizing industry standards to suit the RD&T data format. The data leaves the black box in the color matching the RD&T symbol, meaning it has been reformatted. Finally, the data is placed in the correct location. The demand data is stored in RD&T, from which requirements are generated within the software program.

The following step, the simulation, is conducted manually in RD&T and depicted utilizing the *manual operation* symbol from Figure 4.3. Further, the human symbol above the activity indicates manual intervention. The output from this activity is simulation results, which are the deviation results from the variation analysis conducted in RD&T.

The simulation results are the input to black box B.1, where the results are compiled. The relevant data is then collected from RD&T and reformatted to Excel format. Finally, the reformatted data is placed in the cell containing the results in Excel, leaving the black box as the output.

In black box C.1, the data is analyzed using a script containing a logical function.

The deviation from the simulation results is compared to the assigned tolerance for the demand that is stored in Excel. If the deviation falls within the specified tolerance, the data containing the cell is assigned the color green. The data is then transferred to the next black box, D.1. If the deviation does not fall within the specified tolerance, the cell is colored red. The demand data is looped in the module until the deviation falls within the tolerance and the cell turns green.

The script in black box D.1 is manually started once FDJ is finalized and a prompt is sent to RD&T to keep running the current session containing the results for the approved values. Section points that were created during the simulation in RD&T are stored from earlier, which is indicated using the *stored data* symbol as seen in Figure 4.3. The stored data is utilized in black box D.2, where MP section layouts are created within RD&T. The MP section layouts leave the module as the final output.

Module E: *Semi-automated version*
Module E, visualized in Figure 4.27, addresses area E in Figure 4.25. This covers boxes 2.3-2.6 in the flow diagram in Appendix F.

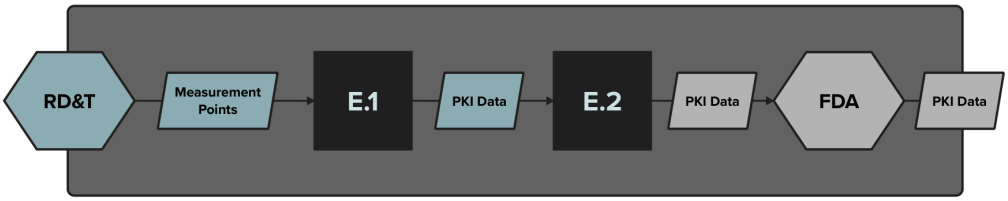

Figure 4.27: Semi-automated version of module E.

The operation within the module is initiated through the obtainment of MP:s in RD&T. With this being the input to black box E.1, the script generates PKI:s and creates JPEG and text files containing the PKI data. In this step, the engineer is required to intervene manually, as the program prompts them to ensure the suitability and correct placement of the chosen gauge for the PKI. Once the engineer approves the gauge, the program keeps running. The output from E.1 then flows through another black box, E.2, where the data is reformatted to fit the FDA interface. This is performed with the help from industry standards for data exchange, as presented in Section 2.3.2, and ultimately placed accordingly into the software. This operation eliminates the need to generate and export the PKI data manually from RD&T, handing it over interdepartmentally and finally implementing it into FDA manually.

4.4.2.2 Possibility for Future Advancement

In addition to the formulated API, opportunities for future advancement and development of the API were investigated. This led to a more automated API where even less manual handling is necessary. However, this version of the API is intended for future use and is not currently feasible given the available technology and resources.

It is intended to serve as an upgraded version of the API presented in Section 4.4.2.1, where advanced future technology is utilized. Such technology might include more complex APIs where artificial intelligence is incorporated to support the engineers.

Module ABCD: *Fully automated version*
The second version of module ABCD is fully automated, meaning there is no manual operation required within the module. The diagram visualizing the module is seen in Figure 4.28.

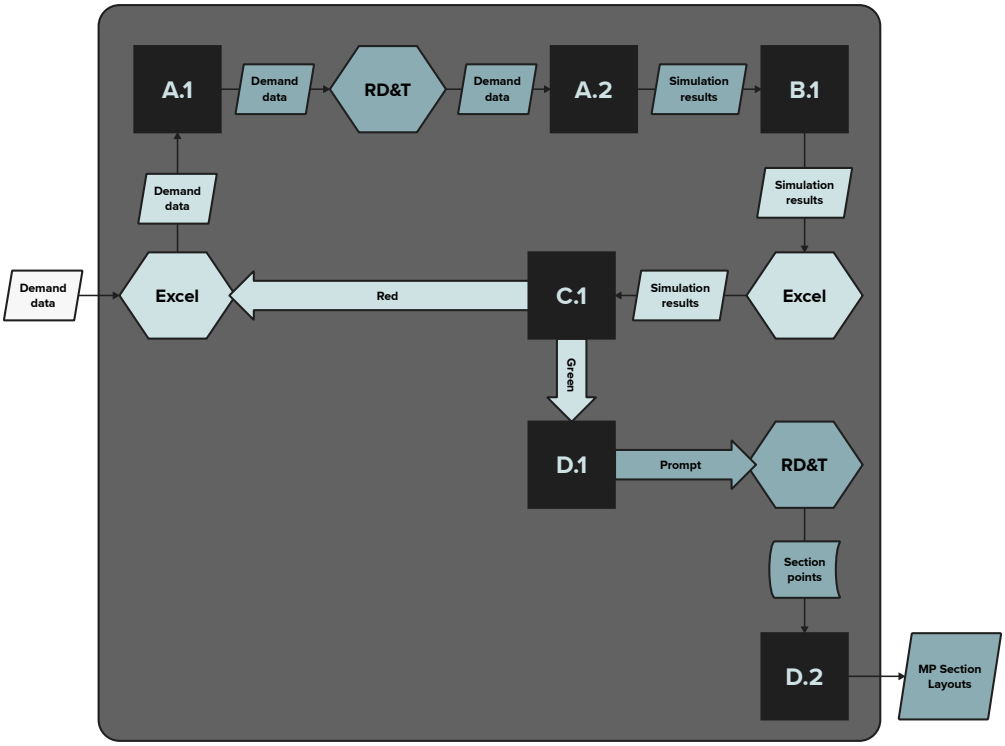

Figure 4.28: Fully automated version of module ABCD.

What distinguishes the fully automated version and the semi-automated one is the substitution of the manual operation where the simulation is conducted with another black box, A.2. In A.2, the simulation conducted in RD&T, containing the steps between the boxes 1.2-1.6 in the flow diagram seen in Appendix F, is executed automatically. This leaves the operations within the module fully automated, eliminating the need for any manual intervention by incorporating a more advanced MBD standard. Such an operation is currently not feasible with existing technology, as conducting the simulation requires the analysis and expertise of a Geo engineer when building the model. Positioning components, setting up measurements, and establishing tolerances on components and processes must currently be carried out manually.

Module E: *Fully automated version*
The automated version of module E is seen in Figure 4.29.

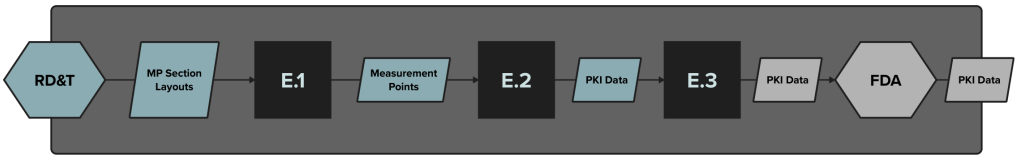

Figure 4.29: Fully automated version of module E.

A difference between the semi-automated and fully automated versions of the API module lies in the incorporation of automated measurement points creation. In the fully automated version, an additional black box, E.1 in Figure 4.29, handles the creation of measurement points, as depicted in box 2.2 in Appendix F. In this step, it is necessary to integrate some form of graphical recognition to determine the direction of the sections, which is not available today.

The purpose of the advanced API with incorporated industry standards is not to replace the role of the engineer. While automation simplifies certain tasks, it does not surpass the engineer's expertise in conducting simulations. Rather, the purpose is to reduce the time and effort spent on these activities, providing support to the engineer. MBD aims to boost efficiency by reducing reliance on manual intervention in processes, thereby speeding up operations and minimizing errors. Although tolerancing and analysis performed by an engineer remain essential, MBD offers substantial assistance in simplifying these tasks, through decreased manual effort [25]. It remains essential for the engineer to actively interfere and control the results and operations to verify their accuracy. Thus, while automation offers efficiency gains, the engineer's involvement is still crucial for ensuring the quality of the outcomes.

4.4.2.3 Process Optimization Suggestions

The identified process-related suggestions are presented in the following list. The solution suggestions address the improvement areas presented in Section 4.4.1.2 and are derived from the facets discussed in Section 4.2.

a. *Well-defined Deadlines and Deliveries*

b. *Evident Process for Feedback and Iteration*

c. *More Efficient Storing and Traceability of Data*

d. *Official Agreements on the Work Process*

e. *PQ Department and/or Attribute Leader*

a. Well-defined Deadlines and Deliveries

Suggestion *a* would partially address improvement areas 1, 3, 6 and 7, presented in Section 4.4.1.2. One suggestion for a solution is to develop a comprehensive time plan with buffered deadlines. For instance, including a buffer of 2-3 weeks can help mitigate delays and maintain progress within the time plan. Additionally, a detailed

time plan should outline key checkpoints or gates in the process, with each gate's deliverables clarified in the preceding one to ensure clarity and prevent confusion.

It is crucial for the team to discuss tasks and responsibilities leading up to each gate, anticipate potential issues and determine if any adjustments or additional resources are needed. Documentation of gate meetings in a centralized location, such as SharePoint, ensures that meeting notes are easily accessible for reference if needed.

Implementing well-defined deadlines and deliverables has multiple benefits. Firstly, it enhances accountability and fosters a sense of ownership among team members, leading to improved performance and adherence to deadlines. Additionally, proactive risk management practices, such as reallocating resources or adjusting timelines to better handle delays, help in identifying and addressing challenges.

Moreover, regular check-ins and feedback loops promote an iterative approach, facilitating continuous improvement and ultimately resulting in a more competitive vehicle design. Clear deadlines also enhance transparency for end customers, ensuring timely deliveries and improving customer satisfaction. In today's rapidly changing market, timely deliveries are essential for maintaining competitiveness and brand relevance.

b. Evident Process for Feedback and Iteration
This suggestion would be applicable for improvement areas 4, 5, 6 and 7, which is presented in Section 4.4.1.2. Implementing a process that incorporates clear feedback mechanisms and iterative practices would offer numerous benefits for Polestar by fostering continuous improvement.

Primarily, establishing regular feedback loops with determined routines, such as sprint reviews or daily meetings enables the team to exchange insights, find areas for enhancement and provide support, somewhat aligning with solution *a*. This facilitates the division of work into smaller, more manageable increments. Regular evaluations also enable the team to easily identify bottlenecks, inefficiencies or other challenges. Moreover, this approach promotes flexibility and adaptability within the process, allowing the organization to respond quickly to changing demands or obstacles. This, in turn, pursues a sense of shared ownership, with all team members working towards a common goal.

c. More Efficient Storing and Traceability of Data
To facilitate more efficient storage and traceability of data, the company could maximize its utilization of the existing *SystemWeaver* database and establish standardized workflows around it, addressing improvement areas 6 and 7, presented in Section 4.4.1.2. It would offer a structured approach to data management, allowing for specific categorization and easy traceability, thereby ensuring transparency and accountability. By promoting the use of this system and fostering a culture that values technical documentation, the organization can establish a centralized platform for storing and sharing data. This facilitates more efficient collaboration and

information sharing across teams.

Further, integration or enhancement of a PLM system, such as the existing *TeamCenter* platform utilized by Polestar for various purposes, could be considered for the GA process. Leveraging TeamCenter as the primary platform for data storage and sharing, rather than relying on methods like email, would offer benefits such as traceable communication, simplified version control and a more robust change management process. Ultimately, this would lead to increased efficiency and productivity within the GA process.

d. Official Agreements on the Work Process
This proposed suggestion addresses improvement areas 5, 6, and 7, as outlined in Section 4.4.1.2. By implementing official agreements within the work process, it promotes a common understanding and facilitates proper handovers and handshakes. The significance of having official agreements lies in promoting clarity and accountability. Employees are provided with clear guidelines regarding tasks and responsibilities, reducing the risk of misunderstandings and ensuring alignment on expectations. Further, establishing a common agreement can be attained through the implementation of the other suggestions, as it can be regarded as an outcome of the other changes.

e. PQ Department and/or Attribute Leader
Suggestion *e* would address improvement area 2, as outlined in Section 4.4.1.2. Implementing a PQ department within the organization would yield several benefits for the GA process. Firstly, it would provide crucial support to the R&D Geo team, alleviating their workload and allowing them to focus more effectively on their tasks. In this way, the specification of demands would be more consistent and steady as it is performed by the same team. Additionally, insights obtained from interviews with engineers at other companies, see Appendix G, underscore the importance of a PQ department in ensuring the delivery of a well-built product as they give attention to every detail. Without such a department, the holistic perspective required for producing cars may be compromised.

4.5 Proposed Process

Through the formulation of the solutions for improving the data flow and suggestions for enhancing the process, the description of the proposed new process can be provided. The proposed process entails implementing the API presented in Section 4.4.2.1 and incorporating the suggestions discussed in Section 4.4.2.3. The proposed process aims to address the identified bottlenecks and inefficiencies present in the current process presented in Section 4.2. It represents the detailed and final solution derived from brainstorming and related activities. A data flow diagram of the proposed process can be seen in Figure 4.30.

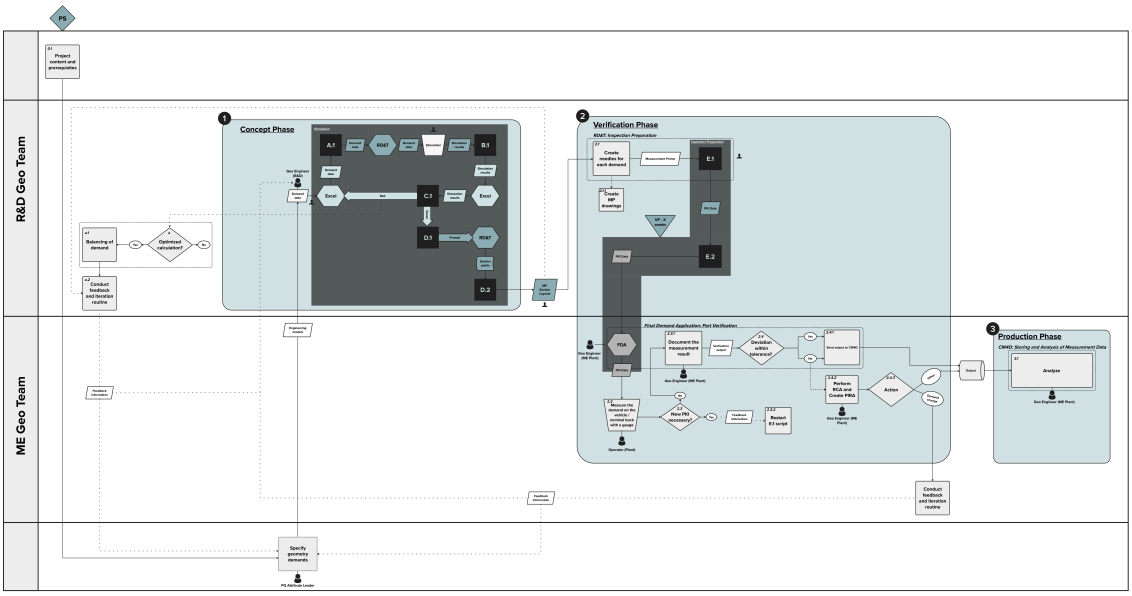

Figure 4.30: Data flow diagram of the proposed process.

The specification of the geometry demands is managed by the PQ attribute leaders. Their task is to alleviate the workload from the R&D Geo team by handling the gap and flush demands with a PQ perspective. Upon receiving the demand data from the PQ department, the R&D Geo engineers initiate their work within the Concept Phase of the final demands management in the GA process. The majority of the work in this phase is managed through the API, where the two modules described in Section 4.4.2.1 can be found. In the created interface, module ABCD is denoted *Simulation* and module E is denoted *Inspection Preparation*, in accordance with the operations executed by the respective modules. The mock-up of the user interface of the API will be accessible through a website where the user first will be asked to choose a module, based on the phase the user wants to work in, which can be seen in Figure 4.31 below.

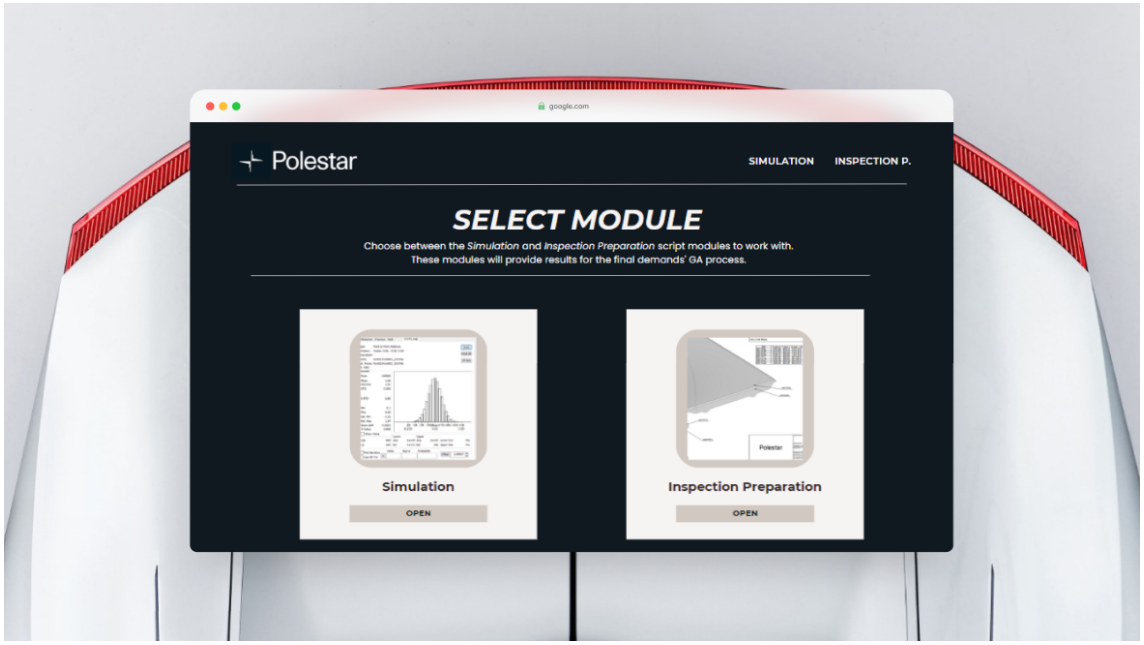

Figure 4.31: Mock-up of start-page of the user interface.

Here, the first page of the interface is shown, where the user is prompted to select a module and thereby open it. For instance, if the user chooses to select the Simulation Module, new decisions need to be made by the user which is depicted in Figure 4.32 below.

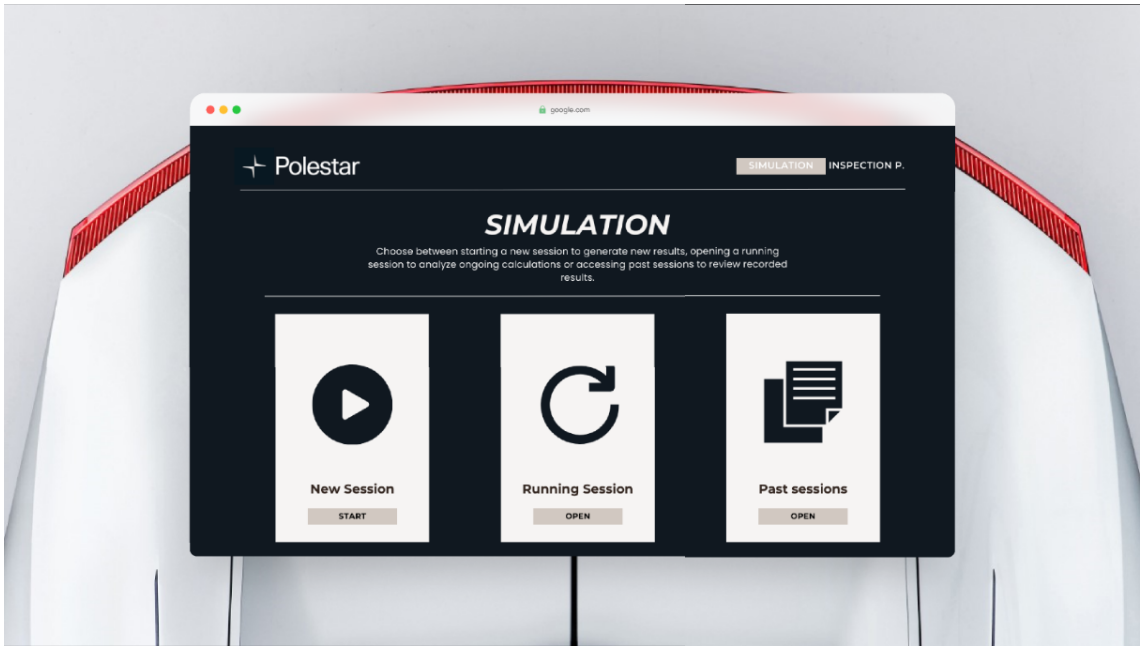

Figure 4.32: Choice of session in user interface.

On this page, the user has to choose to either start a new session, open a running session or see the results of past sessions. In the case of the user starting a new

session, a new page will be prompted where further decisions need to be made, see Figure 4.33 below.

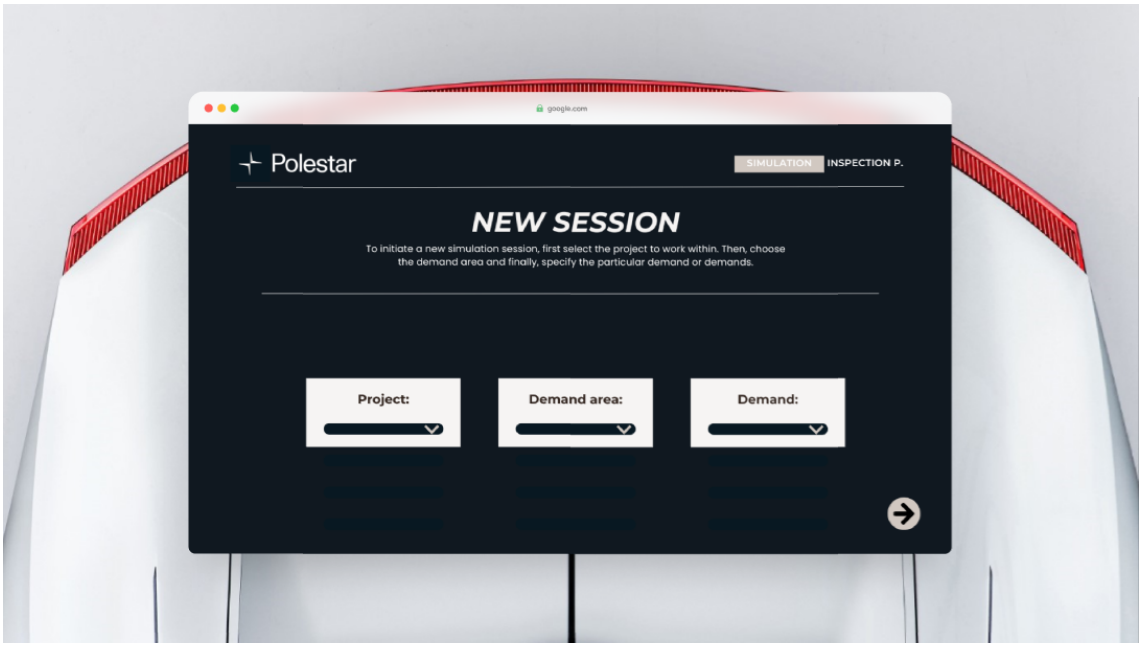

Figure 4.33: Required fields to prompt the simulation module.

In the new session page, the user needs to interact with the drop-down menus of the three required fields in the following order: *Project*, *Demand area* and *Demand*. The Project field drops down a menu of different development projects, once choosing the project the second required field is accessible to be interacted with. There, the demand area needs to be chosen, for instance, the rear body side, which enables the drop-down menu alternatives of the third required field that lists all the demands related to that demand area. Once the three required fields are filled in, the *next page* icon on the lower-right corner can be clicked, which yields three new required fields that can be seen in Figure 4.34 below.

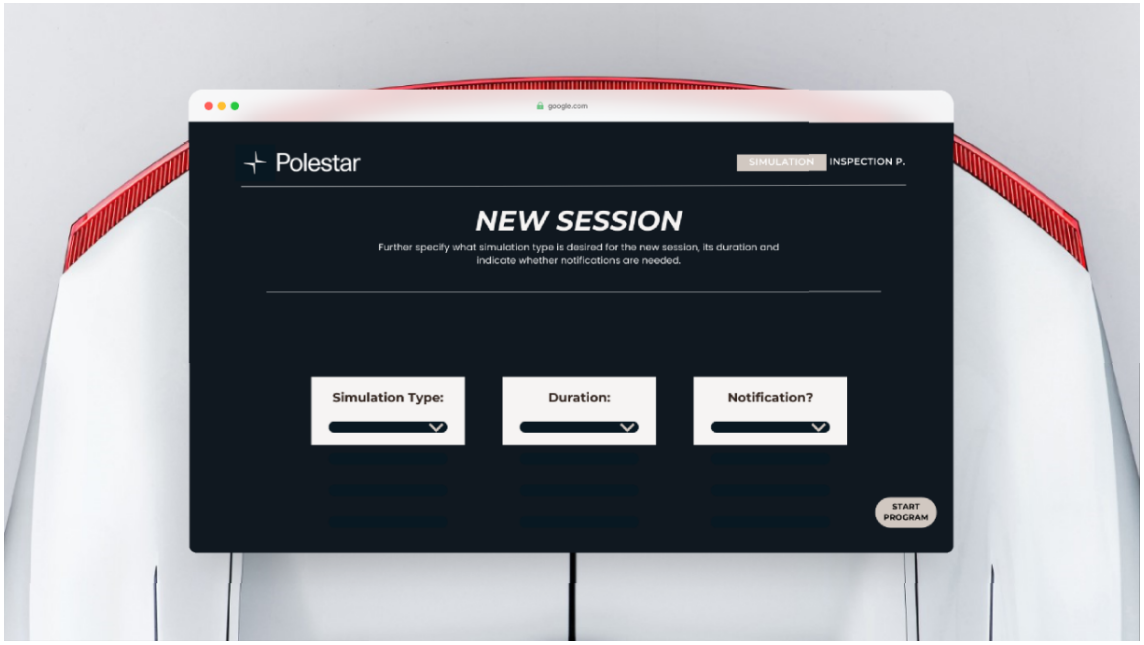

Figure 4.34: Additional required fields to prompt the simulation module.

The first required field that is accessible right away is the *Simulation Type* bar, where the user needs to choose what type of analysis needs to be done in RD&T, whether it is variation, contribution or both. Next, the second required field needs to be filled in which answers the question of how the session should run thereby asking for its duration. The user needs to choose between running until diagnosis appears or running until the session yields affirmative results of the calculations. The last required field is asking the user if it wants a notification by email about the running session or not. Once these are filled in, the program can be started by clicking on the button in the lower-left corner.

The Concept Phase of the proposed process, which can be seen in Figure 4.35 below, is initiated through the selection of the Simulation Module. Similar to the existing process, the demand data is stored and managed in Excel. However, with the implementation of the Simulation Module of the API, entering the data manually is only necessary initially, as the demands are updated automatically and synchronized between Excel and RD&T. The manual intervention is marked with a human symbol, as seen in Figure 4.35. With the demand data entered into the Gap Plan, the Simulation Module can be run by the engineer.

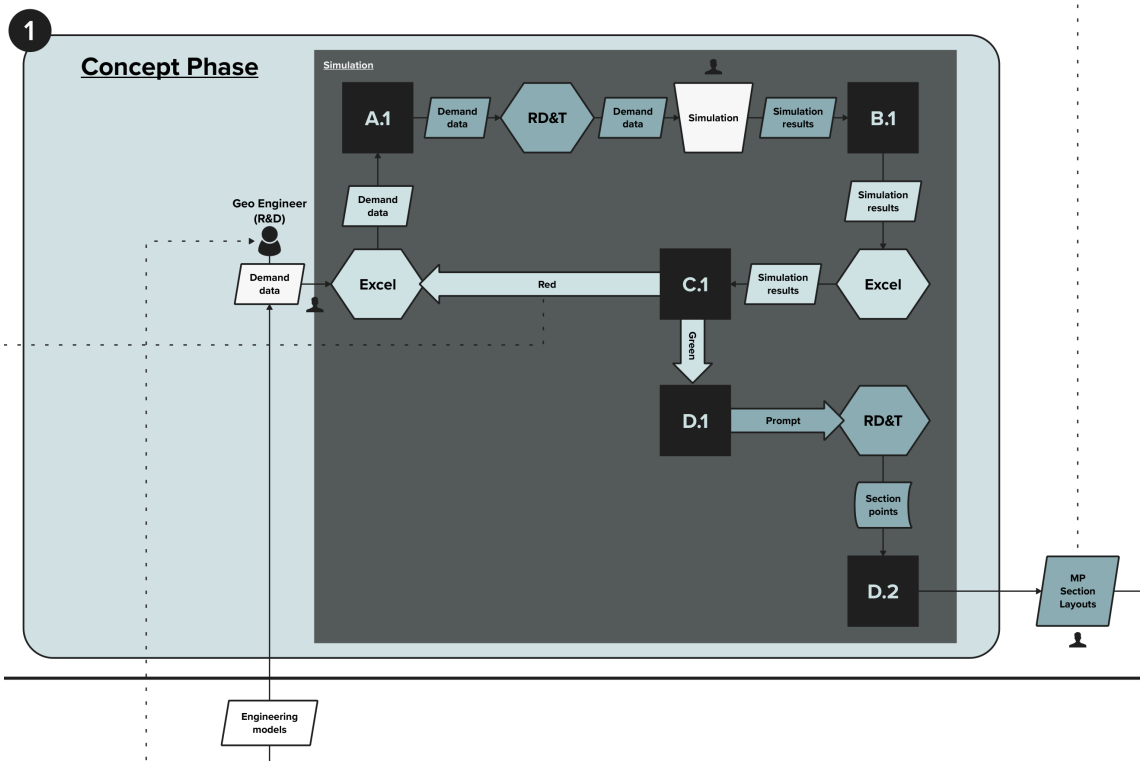

Figure 4.35: Concept Phase of the proposed process.

Given that the semi-automated version is running, the engineer will receive prompts to manually execute the simulation while the module is operating. However, the engineer will be provided with feedback information related to the analysis of the deviation results in black box C.1, described in Section 4.4.2.1. This will be addressed through an evident routine for feedback and iteration. For example, by setting the duration of the API, as seen in Figure 4.34, an engineer may specify that the session continues until it achieves a "green" status. In this case, the session will run until receiving affirmative results in black box C.1, then proceed to black box D.1, and so on. In the proposed process, the feedback process will be incorporated by introducing a routine, similar to a sprint review, after each phase. In this routine, the team presents their findings and issues, involving the PQ attribute leader in the iteration process. By having regular routines or check-ins, the time plan will be well-defined with clear deliverables for the team. Also, to document and store the routine details as well as tracing the process, the database SystemWeaver will be utilized. The database will not only be for the routines but also the complete flow. These implementations will foster official agreements within the process.

Once the Simulation Module has completed operating, the engineer will be presented with the MP section layouts, which require manual involvement as the engineer inspects the sections. Thus, the human symbol is placed in connection to the output of the module in Figure 4.35.

With the completion of the Concept Phase and acquisition of the MP sections, the Verification Phase can commence, which can be found in Figure 4.36. As the Inspec-

tion Preparation Module is chosen for execution, the engineer will begin by creating needles to generate measurement points before running the module. As the module is running, the engineer is prompted to verify the selection of the gauge, ensuring its suitability and correct placement in the PKI. If the gauge needs to be changed, the engineer can interfere and place the gauge manually as desired. At this point, the work of the R&D Geo Engineer is completed and the output of the module is received by an ME Geo Engineer at the plant.

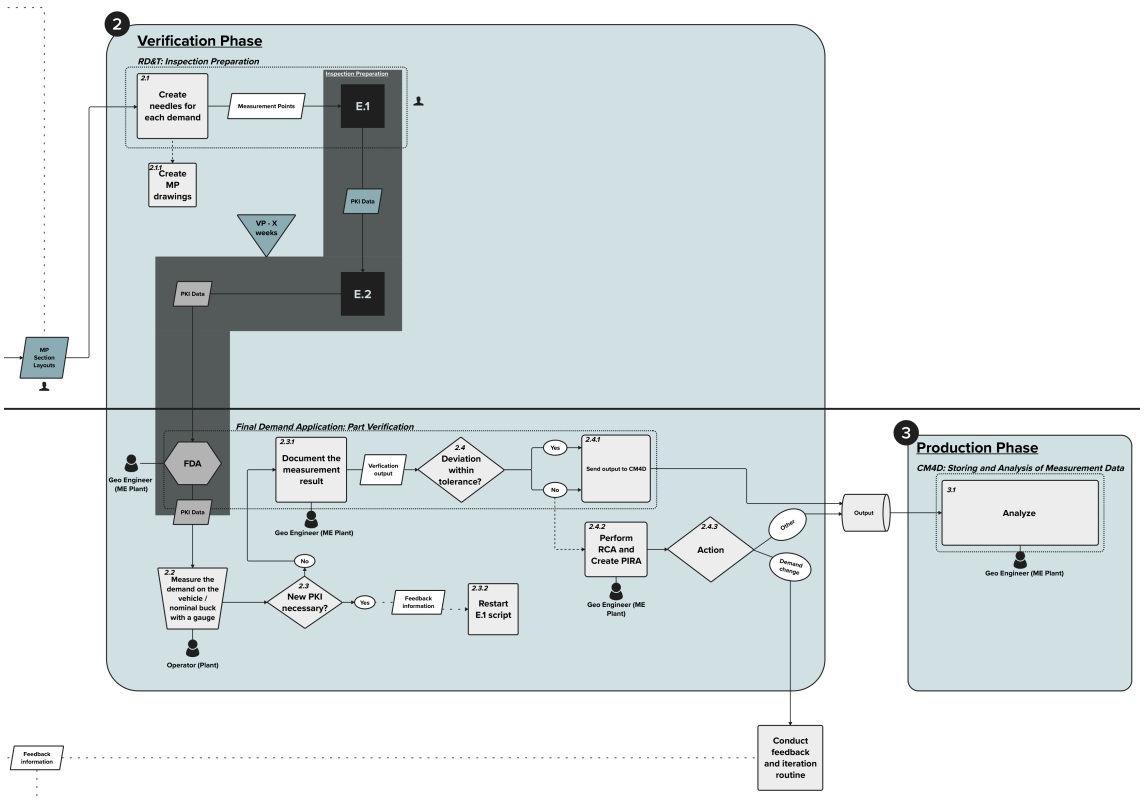

Figure 4.36: Verification and Production Phase of the proposed process.

Once the PKI data is available in FDA, the Geo Engineer at the plant can carry out their work with the part verification. If they find that another PKI is necessary, the script of black box E.1 in Figure 4.35 can be rerun. Further, if the verification results indicate that the deviation is not within the specified tolerance and a demand change is required, a feedback routine will be carried out as described earlier. Lastly, with the output from the part verification available in CM4D, the data is stored and analyzed in the Production Phase, marking the end of the data flow.

4.5.1 Assessment of Proposed Process

To evaluate the proposed process and partially validate the API proposals, the results were shared with a programming expert [40] experienced in working with various scripts and APIs. By presenting the proposals to obtain validation regarding

their feasibility, the proposed process underwent assessment, as summarized in Table 4.5 below.

Table 4.5: Assessment of the proposed process' feasibility [40].

Areas in the API	Feasible?
Reformatting and sending between different softwares	
Iteration until obtaining desired results	
Create MP sections	
Automatic selection of gauge, which is controlled and placed through manual intervention	

The table presents the proposed areas in the API for the proposed process, along with color-coded indications of their assumed feasibility in the current technological possibilities of coding. The green color indicates feasibility, while the yellow color suggests that further investigation is needed, but that feasibility is not far off. As seen in the table, the automatic creation of MP sections is yellow-marked, which is due to the restrictions of graphical recognition for an API, although there is a possibility for it to be solved according to the programming expert [40]. The overall assessment shows a majority of green-marked bars, showing that the proposed process offers feasible improvements.

Further assessment was made by utilizing research articles, see Section 2.3.2, to validate the theoretical feasibility of the proposed process. It was found that existing implementations of industry standards, thereby automated data exchange, imply the possibility of realization of the API. Thus, the assessment was made with the theoretical assumption that the industry standards will be applicable to the API.

5
Discussion

This chapter discusses the advantages and potential challenges of the proposed process, offering insights into its benefits, sources of error, future development opportunities and methodological reflections. Additionally, it identifies and discusses technical and human-induced errors and outlines future directions for process improvement. Furthermore, through a reflection on research questions, it provides conclusive insights into the implications of the study, with a summary highlighting key findings for the reader.

5.1 Advantages of Proposed Process

This section delves into the advantages offered by the proposed process, discussing its potential benefits in detail. Through analysis of both the API's advantages and the broader advantages stemming from the process suggestions, it discusses the value proposition of the proposed approach, providing valuable insights into its benefits.

5.1.1 API

There is a clear indication that the proposed process has great potential to outperform the current one through the implementation of the formulated solutions. Firstly, the API is expected to improve the data flow by mitigating bottlenecks and saving time. As a part of the process will be automated, less manual, time-consuming intervention is necessary. Further, transferring data via the API reduces the risk of human error that comes with manual data handling and reformatting, ensuring higher levels of accuracy and reliability. Utilizing the industry standards presented in Section 2.3.2 for this procedure is assumed to be advantageous for this application, as there are strong implications for success in the paper *Model-based definition in computer-aided tolerance analyses* written by Aderiani, A., Wärmefjord, K. and Söderberg, R. [25]. For instance, the authors argue that incorporating industry standards for automated data exchange would offer advantages in terms of speed and reduction of errors. Thus, the data quality is preserved to a greater extent, meaning that the accuracy, completeness, consistency, and reliability of data over time are maintained. Preserving data quality is crucial for conducting meaningful analysis and achieving reliable results. Additionally, as the API provides standardized interfaces for data exchange, it ensures consistency across all the softwares. Thus, the demand data is linked and is updated continuously across all software programs. This eliminates the need to manually update the demand data every-

where once changes are made, which further implies efficiency and time reduction.

Other advantages of the automation in the proposed process include the traceability of past demand data and results. This is something that works well and is perceived as useful at the competing companies presented in Section 2.4 [20], meaning it can bring value to Polestar's process as well. In the API user interface described in Section 4.5, the user can access past sessions. This allows for the analysis of trends and patterns over time, providing insights into past performance. It supports continuous improvement by allowing for the identification of mistakes, successes and areas for improvement. Further, in case a change needs to be reversed, past demand information can be retrieved.

By eliminating manual data handling tasks, employees can focus their time and efforts on more strategic activities, thus increasing productivity and efficiency within the organization. Automated data management is also a goal pursued by competing companies in order to improve efficiency and save time [20]. Another advantage of implementing the API is a reduction of labor costs of manual activities, resulting in cost savings for the company. This argument is strengthened by the findings in [25], implying that through enabling automation, MBD will decrease the efforts and costs involved in a process similar to the proposed one. Reduced operational costs allow the company to allocate resources more effectively and invest in more significant areas.

5.1.2 Process Suggestions

Implementing the process suggestions outlined in Section 4.4.2.3 promises many advantages within the proposed process. Foremost, the increased utilization of SharePoint as a standard tool ensures effortless access to documentation on changes and meetings, significantly enhancing traceability. In addition to utilizing SharePoint, the proposed process integrates SystemWeaver for data management, which is seen within the process at competing companies [30]. This centralized platform facilitates improved collaboration, further fortifying the advantages of the proposed process. Moreover, instituting a standardized workflow fosters a culture of individual accountability, thus stimulating enhanced performance among team members and, consequently, elevating overall project outcomes. This standardized approach also streamlines adherence to deadlines, offering clarity and direction within the process. Notably, the process's inherent flexibility allows for iterative enhancements, with regular checkpoints and feedback loops fostering continuous improvement.

Regular feedback routines provide a significant advantage for team members to exchange knowledge and advice, aiding in the identification of bottlenecks and challenges. Having regular gates is something that is encouraged at competing companies [20], and by employing this at Polestar as well the work can become more manageable and easier to resolve. This is advantageous for managing adjustments in the timeline and minimizing delays. Further, the improved punctuality in meeting

deadlines, facilitated by the proposed process, strengthens the company's competitiveness by minimizing disruptions and delays. This ensures the company's relevance and responsiveness to changing market demands, granting it a competitive advantage. It becomes evident that the proposed process is more adaptable and flexible with all team members working toward a common goal.

Furthermore, the proposed process involves establishing a PQ department in the GA process, illustrating its advantages over not having one. Primarily, integrating a PQ perspective enhances work performance by alleviating some of the responsibilities on the R&D Geo team and providing a clearer delineation of expectations for each team and department. This clarity represents a distinct advantage over the current process. Additionally, the presence of a PQ department is beneficial in fostering the development of higher-quality products, as highlighted in the interviews, see Appendix G.

5.2 Constraints of Proposed Process

This section presents a thorough investigation of the sources of error within the proposed process, focusing on the categorization of these errors into human and technical barriers. The section aims to provide a comprehensive understanding of the potential challenges associated with implementing the proposed process.

5.2.1 Technical Constraints

While the proposed process offers significant advantages for the company, it also presents some technical barriers that must be overcome. Primarily, integrating the API and connecting existing software may pose challenges, as it introduces complexities. These challenges could appear as compatibility issues or technical constraints, necessitating detailed planning before implementation. As the proposed solution was formulated, an assumption was made that the deployment of the API would be realizable using the industry standards for data exchange. Additionally, there may be challenges associated with deploying the software across different geographical locations, complicating compatibility and emphasizing the need for web-based solutions that ensure consistency across the systems. Further, the separate locations could present difficulties in identifying errors within the program, as the process is handled by different teams. Furthermore, implementing an API program for data sharing between different systems can raise concerns regarding data security and privacy. To address this technical barrier, robust security measures should be implemented to protect sensitive information and data.

Moreover, the user interface of the API program can significantly influence productivity and adoption. A complex or poorly designed user interface can be disadvantageous, potentially leading to errors or resistance from users. Therefore, thorough user testing is necessary to gather feedback and subsequently improve the interface. Another barrier that could be disadvantageous when implementing the proposed process is the dependency on the API program. For this reason, performance is

of great importance, as a slow or disrupted system could decrease operations and impact overall productivity in a project. To manage this technical barrier, some kind of regular maintenance is necessary to avoid major errors and slowdowns.

The proposed process also implies that integrating a PQ department is advantageous. However, the specifics of how they should operate and how they will be integrated into the process are not yet determined. This could present a complex challenge if implemented. Therefore, thorough planning is necessary to detail how they will be incorporated to ensure that their inclusion becomes an advantage. A similar argument applies to the implemented feedback routines in the proposed process, they are not specific enough to be readily used and incorporated, which could present another barrier.

5.2.2 Human Constraints

There are some barriers to implementing the proposed process associated with human factors. Firstly, while the API is a reliable and efficient tool, there is a risk that engineers may become overly reliant on it. They might oversee errors and mistakes in the results generated by the API, by failing to intervene manually when it is recommended or required. This might cause them to become less skilled at problem-solving, which can hinder their ability to address unexpected issues and operate effectively without the support of the API. Further, the engineers may lack understanding of the underlying principles of GA when relying solely on the automated solution for simulation, tolerancing and inspection preparation. As a result, the expertise within the company may become weakened if tools such as the fully automated version of the API are not used wisely.

Introducing changes to an existing process typically involves providing employees with training to effectively utilize new tools and systems. Insufficient training or unclear instructions on how to use the API interface may result in errors, frustration, and reduced productivity. Although support can be provided, another barrier might include resistance to change by the employees. Employees may be used to existing processes and may resist adopting new technologies or methodologies due to uncertainty. A key finding obtained in the project from studying the current process is that many Polestar employees have developed individualized work methods that they perceive as optimal. Consequently, they may express resistance to change and might not be comfortable working according to a standardized process. This might result in some individuals choosing not to comply with the designated process. Thus, a common understanding of the need to introduce changes within the organization is essential in order for the changes to be feasible.

Establishing a new department, such as the PQ department, will require plenty of resources in the form of personnel, equipment, softwares and tools. This issue could be resolved by starting small and introducing the PQ perspective, initially involving only a few experts working with PQ. Additionally, physical resources such as office space are required. Another barrier might be integrating a new department with

the already existing departments at the company, and synchronizing their workflows. As seen in the results presented in Chapter 4, several departments and teams work together throughout different phases of the GA process at Polestar. Due to this, some barriers might arise. Since each team has its own areas of responsibility, operations and deliverables, introducing changes that are suitable for each stakeholder is challenging. Further, there are several elements of their work, both related to the GA process and other processes, that are not addressed or studied in this project, making it difficult to define solutions that will take every aspect into consideration. In addition to this, as Polestar is a global company with employees in Sweden, China and the UK, cultural or geographical barriers within the organization might lead to different levels of acceptance. Thus, the efficiency of the proposed process may vary across different departments and regions.

5.3 Future Development

In the future, the proposed process can be further developed by exploring options for additional automation. This could involve implementing the fully automated version described in Section 4.4.2.2, which was presented as a potential future extension due to existing technological limitations or unexplored possibilities. Additionally, the proposed process, or semi-automated version, needs future refurbishment too. Future development of the semi-automated version is needed as the suggested automatic creation of MP sections needs to be investigated and solved, which is possible to solve in the near future but not today. However, the future extension, the fully automated version, is not impossible to be of favor and feasible in the future.

However, to develop the fully automated version, additional technologies need to be incorporated in the future. For the API to perform operations like recognizing and building a model, or graphically determine where a gauge needs to be placed, more advanced technology needs to be investigated. With existing technology, it remains uncertain whether it is adequate for automating the entire CAT process or to what extent the process can be automated, as stated in [25]. Therefore, future development should focus on exploring emerging technologies within the automotive industry and software engineering to identify their applicability to the proposed process.

An essential step to realize the implementation of further automation is to advance the industry standards in order to ensure compatibility with various software, thereby enabling standardized interfaces for data exchange. Furthermore, investigations should also focus on determining whether tools such as artificial intelligence, the Internet of Things or machine learning can enhance the efficiency and effectiveness of the final demand data management. Exploring the incorporation of artificial intelligence to allow the API to run the whole simulation would be of favor and its feasibility is worth investigating in the future. Such advancements have the potential to result in a less time-consuming process, ultimately elevating the quality of the end product. However, the integration of artificial intelligence or industry standards

is not intended to replace or assume all the tasks and responsibilities of an engineer. Instead, it serves as a supportive tool utilized by the engineer to streamline processes and reduce labor time, which also is articulated in [25].

Moreover, the proposed process can be further enhanced by establishing key performance indicators, KPIs, to track its efficiency and effectiveness in comparison to the current process. For instance, KPIs could be established to measure the reduced time-to-market, cost savings or increased revenues resulting from the proposed changes [41]. This will enable a quantitative assessment of its performance.

5.4 Methodology of the Project

This section provides reflections on the methodology and work process of the thesis. As described in Section 3.1, the methodology approach of the project followed a structure of three key phases that include *Preparation, Realization* and *Analysis*. It can be concluded that this was a favorable approach, as it provides clarity and structure by dividing the project into distinct phases. It enabled thorough planning and resource allocation in the Preparation Phase, facilitating an effective execution in the Realization Phase. This included conducting a proficient literature study addressing resourceful literature. The selection of theory in the literature study was beneficial for the project, as it provided valuable support for the methodology approach. Further, it contributed significantly to the outcome of the thesis as it provided a deep understanding of the subject. Finally, the Analysis Phase could be carried out successfully as the past phases had generated a useful foundation of results.

The methods selected for the project were well-suited and generated valuable results. Certain adjustments were made to the standardized product development methods to better align with the project's objectives. This can be seen in Section 3.4.2.2, where the 5 Whys method was modified to suit the objectives of the thesis. Given that the project focused on processes and data flow rather than physical product development, these modifications were necessary to align the approach accordingly.

5.4.1 Sources of Error

Despite the benefits of the chosen methodology, there were still some sources of error that could have influenced the outcomes of the report. The identified sources of error primarily concern the interviews and Pilot Study, along with other uncertainties.

Firstly, interviews, being a qualitative assessment of information, introduce the possibility of partiality among responses, as each interviewee may answer based on their individual opinions and experiences. Additionally, there may be bias in the selection of interviewees, as they were chosen based on their reputed experiences, potentially resulting in biased information gathering. Similarly, the limited number of interviewees may not sufficiently represent the voices both within and outside the company. Furthermore, some selected interviewees were geographically located

in other countries, possessing cultural and linguistic barriers from the interviewers. This situation may have led to miscommunication and interpretation issues regarding both the questions asked and the answers provided, potentially resulting in unnuanced information gathering from those interviews. Likewise, misinterpretation of responses could have occurred in all interviews, whether through human interpretation during transcription or automatic transcription errors. This could potentially have led to overlooking important content and patterns among the interviewee responses in the collected interview data.

Secondly, the execution of the Pilot Study also revealed sources of error. Initially, the conducted Pilot Study represented a very small-scale version of the actual GA process and the data flow of final demand data within that segment, differing from its practical implementation. This differentiation may have influenced the comprehension and perception of the process, potentially leading to inaccurate outcomes. This could have led the researchers to overlook the holistic perspective of the current process. Additionally, in practice, the process involves iterations and loops back and forth several times. However, in the Pilot Study, this iterative aspect was not replicated multiple times, potentially leading to incomplete information gathering of the process. Further, the approach to feedback and iteration in the current process was not studied in detail. If conducted with greater consistency to the actual process and with more iterations, the outcomes might have been more comprehensive.

Lastly, additional sources of error were identified in the methodology, potentially impacting the final results due to uncertainties they introduce. The studied data flow and process represent only a small segment of the entire GA process, focusing solely on the management of final demands. This limited scope may have influenced the researchers' perceptions, hindering a comprehensive understanding of events occurring before, after and during the process. The outcomes resulting from this error may have been less favorable. Conducting a more comprehensive and in-depth study of the entire GA process had the potential to enhance understanding and improve outcomes. This could be followed by a focus on the final demand data flow, as there are more factors outside the scope that need to be accounted for. Moreover, uncertainty in the methodology lies in the absence of further validation for the proposed process, such as through an implementation, digital prototype or pilot running. Even though there was a type of validation made, it could have been extended to increase the reliability of the validation results. If further implementation for validation were included in the methodology, it would provide a clearer understanding of the proposed process and its practical benefits could be documented.

5.5 Research Questions

In the following section, the three research questions stated in Section 1.4 are revisited. The findings that address these questions are examined and discussed in terms of providing answers to the stated questions.

5.5.1 RQ1

The first research question is the following:

What is the approach to current practices and documentation methods, including specification and management of demand data throughout the geometry assurance process at Polestar?

A significant objective of this thesis was to study the current approach to the GA process at Polestar, with a focus on management of final demand data. This was accomplished by mapping the different phases and steps in the process, which involves various teams and departments. The process was studied in segments according to the theory presented in Section 2.1.2, which includes the Concept, Verification and Production Phase. Tasks were carried out within each phase and the responsible teams were mapped in a flow diagram.

During the Concept Phase, the R&D Geo teams in Sweden and the UK play a central role, primarily engaging in simulations within RD&T. This involves extensive manual handling and transfer of the demand data between the Gap Plan in Excel and RD&T. Additionally, the R&D Geo team initiates the Verification Phase by creating inspection preparation documents, which are then forwarded to the ME Geo team in China. The ME Geo team utilizes FDA for part verification, employing measurements taken on a vehicle or nominal buck. Subsequently, the measurement data is stored and analyzed in CM4D in the Production Phase. Standardized work routines are generally lacking in the current process, especially in the Concept and Verification Phases, which tend to rely more on individual-based approaches.

5.5.2 RQ2

The second research question is articulated as:

What bottlenecks are present in the data flow of the current geometry assurance process at Polestar?

Through the examination of the current process at Polestar, bottlenecks impairing the data flow and overall process efficiency were identified. These insights stemmed from interviews with involved employees, studying the process activities and from conducting a Pilot Study. The findings obtained from these activities were facets revealing areas and steps in the process requiring improvement. This mainly includes poor time management, lack of clear deadlines and deliverables, lack of routines and standardized processes, the absence of a PQ department and notably, manual and unstructured management of demand data. The bottlenecks stemming from extensive manual data transfer in the data flow were identified within the process, primarily occurring in the Concept Phase of the project and partially in the Verification Phase. The primary data challenges within the Concept Phase were the frequent switching between the Gap Plan in Excel and the RD&T software, the iterative looping of simulations within RD&T, and ensuring the linkage of all demand

data across all programs.

5.5.3 RQ3

The third and last research question is as follows:

How can the current practices employed in managing demand data in the geometry assurance process be improved, and how can these enhancements be integrated into the existing and future framework at Polestar?

This study set out to formulate solutions and suggestions on how the current process can be enhanced, and how these improvements can be integrated practically. During the project, identified bottlenecks and areas for improvement were tackled, and corresponding solutions were provided. This is reflected in the outcome of the solution development process. As a result, an API for automated data management in parts of the GA process was developed, alongside recommendations for general process improvements. Implementing the API serves as a method to improve the data flow and address bottlenecks by automating data transfer and preserve the data quality. This eliminates the need for extensive time-consuming manual data handling. Further, process improvements in the form of establishing additional departments and incorporating routines are thought to improve the current practices in the GA process at Polestar. This elevation is expected to enhance the overall performance of the process. A description specifying how the solutions can be integrated into the process has been outlined through the definition of a proposed process. However, given the project's constrained time frame and expertise limitations, a comprehensive plan detailing how to practically integrate these improvements and how the API should be deployed has not yet been formulated. This is essential in order to verify the effectiveness of the solutions and achieve the desired outcome, which is process improvement. Therefore, it is advisable to outline a strategic plan for integrating these aspects into the existing and future framework at Polestar.

5.6 Summary

Based on the aspects that have been discussed, it is evident that the proposed process holds the potential to significantly improve the current approach at Polestar. Through the implementation of formulated solutions, such as the API for automated data management, opportunities for improvement are identified. The API is expected to improve the data flow, reduce manual intervention, and enhance accuracy and data quality by minimizing human errors. Moreover, it offers standardized interfaces for data exchange, ensuring consistency across software programs and reducing the need for manual updates. Thus, the findings obtained from this master's thesis may offer valuable insights for future research and development related to automated solutions for digital data management. Further, the reflections presented also emphasize the advantages of the process suggestions, which contribute to improved overall performance. There is considerable potential for the proposed

solutions to offer value to the organization at Polestar. However, the implementation of these solutions faces challenges, including technical complexities, resistance to change, and resource requirements. A lack of strategic validation and testing may impair the feasibility of the solutions. Additionally, sources of error in the methodology, such as interview bias and limited scope, are acknowledged, suggesting areas for future refinement. The importance of a strategic plan for integrating enhancements into Polestar's framework is emphasized, exemplified by proposing the fully automated version as an extension of the proposed process in the future. Additionally, opportunities for future development and additional validation are discussed.

6
Conclusion & Recommendations

The master's thesis primarily aimed to improve the data flow and final demand data management in Polestar's current geometry assurance process. This involved identifying bottlenecks and proposing strategic improvements to enhance overall efficiency. Consequently, the thesis aimed to examine the existing process, map areas for enhancement, and refine the process by formulating improvements to the current approach, while also considering future practices. Based on the results and conducted analysis, it can be concluded that the primary aim of the thesis was achieved. Through the study, the phases of the current process were examined and the data flow could be mapped. This was done through interviews and by conducting a Pilot Study, with support from a literature study of relevant topics. Key bottlenecks and areas for improvement in the flow were identified, caused mainly by manual data handling and a lack of standardized routines within the current process. Strategic improvements were formulated by utilizing techniques and systematic methods for generating solutions. Through the proposed strategic improvements, which include an API for automated data management along with additional process enhancements, clear routes for improving the overall efficiency of the data flow and performance of the process were outlined. Additionally, a proposal for future advancements of the API utilizing uprising technology was presented.

The proposed API facilitates automated data transfer and formatting utilizing industry standards between softwares Excel, RD&T and FDA, linking the demand data across all software programs. The demand data stored in Excel is automatically transferred to RD&T, where manual simulation conducted by an engineer produces deviation results. The resulting data is analyzed by the API and a script is run in RD&T to create section layouts. With support from manual intervention by the engineer, an inspection preparation is conducted in RD&T. The output data is reformatted by the API to suit the FDA interface where the part verification is carried out, eliminating the need for manual PKI data export. The suggestions addressing the improvement areas within the process include the establishment of standardized work routines, incorporation of efficient time management and including a PQ perspective in the concept development.

Although the thesis has progressed considerably in fulfilling its objective, it is essential to acknowledge certain limitations and areas for further refinement. The potential sources of error identified in the methodology and the need for further validation of the proposed process underscore the importance of ongoing research and development efforts. For instance, the need for a comprehensive plan detailing

the practical integration of proposed improvements, including the deployment of the API, remains a critical aspect for future consideration. Hence, it is advisable for Polestar to explore the possibilities and create a strategy for integrating the proposed solutions. Individuals skilled in software development and programming should continue the further development of the API. In addition to this, senior management at the company should proactively foster the new culture associated with the proposed process. With all these considerations in place, it is advisable to deploy and implement the API for final demand data management within the geometry assurance process at Polestar. After a successful implementation of the proposed process and its seamless integration with other company operations, Polestar should prioritize further investigation into applying the fully automated version as emerging technologies evolve.

In conclusion, the master's thesis successfully achieved its primary aim of providing solutions for improving data flow and final demand data management within Polestar's geometry assurance process. Through strategic improvements and proposed enhancements, clear pathways for enhancing efficiency were delineated, paving the way for future advancements. With the findings obtained from this thesis, clear potential for the integration of emerging technology is showcased and future innovation at Polestar can be fostered.

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A

Appendix A. Interview Guide for the Preparatory Interviews

Appendix A presents the interview guide created as a reference for the preparatory interviews. It includes questions categorized into different subheadings: work-related questions in the geometry assurance process and problem-related questions. In total, there are 26 questions starting from zero, with some containing sub-questions.

Interview Guide for Preparatory Interviews

0	Is it okay to record your answers? All material will be deleted by June 2024.
Work-related questions - GA process	
1	What is your current role and how long have you been working as it?
2	Have you had other roles related to geometry assurance?
3	What software and systems do you use during the process? Tools? a) For GA activities b) For storing requirement data
4	What are your tasks and responsibilities?
5	Explain the work process that you follow
6	How do you work with requirements in your role?
7	What are your deliverables? a) In the form of documents?
8	What requirement data do you need in order to perform your task?
9	a) Who do you receive data from? (role and / or department) b) How do you receive the data (hand-over of information)?
10	a) To whom do you provide data after completing your task? (role and / or department) b) How do you send the data (hand-over of information)?
11	a) How would you describe the data flow in a geometry assurance process from start to finish? b) In what stage of this process do you place your own tasks and work?
12	How is feedback and iteration carried out in the data flow?
13	How late in the process can changes be made to the requirements? a) How frequently does it happen?
14	How are new requirements verified later in the process?
15	How are old versions of requirement data handled and stored? a) How often do you use them?
16	How is perceived quality integrated in your work process?
17	What kind of requirements related to PQ do you work with?
Problem-related questions	
18	What do you consider the most significant challenge with the requirement data management in your geometry assurance process?
19	In what way can this be improved?
20	Have you noticed other problems or less effective ways of handling the data in the process?
21	In what way can hand-overs of data be managed better and more efficiently?
22	In what way is the process sensitive to variation and deviation?
23	What are the potential consequences of the issues you brought up? For instance; - if the hand-over is not handled well - if documents are missing - changes are made - delays are occurring
24	What do you think works well in the process?
25	How can these aspects be integrated further?
	Final comments

B

Appendix B. Interview Guide for the Interviews with Engineers from Competing Companies

Appendix B presents the interview guide created as a reference for interviews with engineers from competing companies closely involved in perceived quality. It comprises 13 questions, numbered from zero, focusing on geometry assurance related to perceived quality, with some including sub-questions.

Interview Guide for Interviews with Engineers from Competing Companies

0	Is it okay to record your answers? All material will be deleted by June 2024.
1	What is your current role and how long have you been working as it?
2	Have you had other roles related to geometry assurance/PQ?
3	How would you describe "Percieved Quality" and its connection to geometry assurance? a) Why is it important to consider PQ when developing cars?
4	What are your tasks and responsibilities?
5	Explain the work process that you follow
6	How do you work with requirements in your role? a) What type of demands? b) Where do you store and document them? c) How is old versions of requirement data handled and stored? d) Do you find storing old requirement data important/useful?
7	What software and systems do you use during the process? a) For activities related to GA? b) For storing requirement data?
8	How do you define the requirements related to PQ? What is it based on? a) Explain the process from start to end (briefly)
9	In what way is the process sensitive to variation and deviation?
10	How is feedback and iteration carried out in the data flow?
11	What do you think works well in the process in terms of data- and informationflow?
12	Anything you want to add that we could have missed to ask?

C

Appendix C. Interview Guide for the In-depth Interview

Appendix C includes the interview guide prepared to be used as guidance throughout the in-depth interview with a senior geometry engineer closely involved in the early phases of the geometry assurance process. The interview guide comprises 15 questions, numbered from zero, focusing on the engineer's work and the problems encountered within it.

Interview Guide for In-Depth Interview	
Questions	
0	Is it okay to record the meeting? All material will be deleted by June 2024
Work-related questions	
1	What is your current role and how long have you been working as it?
2	What are your tasks and responsibilities? Explain the work process that you follow - How is a PS initiated? - Could you explain the figure for us?
3	What are the tasks of the team you are responisble for?
4	How do you work with requirements in your role? How would you describe a final demand?
5	What are the deliverables of the team that you are responsible for?
6	How do you work with check-ins and gates within your team?
7	How do you work with feedback and iteration? - With component owners? - With other teams?
Problem-related questions	
8	In your opinion, what are the most evident challenges within your team? - Particularly when it comes to management of requirement data?
9	What are some issues that can impair the data quality?
10	Are there any time-consuming bottlenecks present in the process?
11	What are the greatest strengths within your team?
	****Discuss interview results - challenges****
12	Do you agree with these statements?
13	What do you think is the reason behind this?
	****Discuss interview results - imporvements****
14	Why do you think these improvements would or would not be feasible?
15	Do you have any other possible improvements in mind?

D

Appendix D. The Transcription of the Preparatory Interviews

Appendix D presents the transcription of the four preparatory interviews with engineers from different phases of the process. The appendix is divided into a *Questions*- and *Answers from interviees* column, which has subcolumns within. The answers column consists of four subcolumns, each representing the transcribed answers from one interviewee. The names of the interviewees are not presented due to anonymity, but their roles are listed in the top row of each subcolumn, along with the phase they work within and the date of the interview.

Transcription: Preparatory Interviews					
	Questions	**Answers from interviewees**			
		Geometry Engineer, early phases (1/2-24)	*Geometry Program Manager, pre-production phase (7/2-24) - translated from Swedish*	*GEO Engineer, production phase (20/2-24)*	*GEO Equipment Engineer, production phase (27/2-24)*
0	Is it okay to record your answers? All material will be deleted by June 2024.	Yes	Yes	Yes	Yes
	Work-related questions - GA process				
1	What is your current role and how long have you been working as it?	Geometry assurance engineer at PE Geometry / Polestar.	Geometry program manager at PE Geometry / Polestar. At ME. Since november 2021.	Geometry engineer at Polestar, China.	I am responsible for all the measurement equipment (also called the Geometry storage system) and I have over 15 years of experience in this field. I work at Polestar since 2020. I am a **GEO equipment engineer in the ME section** but our group is also a part of quality.
2	Have you had other roles related to geometry assurance?	It was all geometry assurance, but **in Volvo trucks, for example, we did the entire chain** from very early on where we look at the design concepts and talk with design a little bit, help with that. Help etting the demand, the gap and flash demands and so on, calculating it. And then industrialization and manufacturing. **In Cevt (and Volvo Cars for instance) we would do the chain up to FDJ** (Final Data Judgement - all data done and manufacturing can take over).	Yes, worked with geometry but not specifically at ME. Worked both at the factory with production and with R&D. I've been a team leader at SAAB.	Three different roles. Geometry engineer, equipment engineer, technician.	Before my current position, I worked for **Geely** and **Land Rover** in the same area.
3	What software and systems do you use during the process? Tools? a) For GA activities b) For storing requirement data	**TeamCenter** - That is where I grab the models and parts that I need to work with. **RD&T** - for simulation. **CM4D** - measurements, It's a database, so suppliers measure the parts and they store it in that database. Niklas is more involved than that than I am, but I use it a little bit as well. **Excel** -	TeamCenter, TcVis, CM4D	**CM4D** for measurement data. We collect results from the plant and the supplier. Checking fixtures. We have a software for measuring gap and flush and collecting visual results. **TeamCenter, sometimes Catia.**	The software I use is called **CM4D,** a Swedish company, from a supplier named ATS. But also **e-mail** .
4	What are your tasks and responsibilities?	Geometry assruance work. **In other companies, we would have more strict deliveriesfor each phase of the project**, - you as a geometry assurance engineer should deliver this. **We lack this at Polestar.** We do what we think it's needed based on a lot of experience, a lot of experience from from Volvo Cars, trucks and Cevt. And when component owners ask for it. Except for one hard delivery that we have had for **measurement point drawings and PKI**, which is the measurement instructions on the final car. **Those deliveries we usually have set dates for.**	Map how the product (hardware) looks and identify what type of documentation is necessary in order for us to make our judgement, and map what kind of tools we need in the factory.	I send feedback, study the response from the measure team that measure the part body and fixture. If we come across issues, we send the feedback to geometry engineers (R&D) to fix it.	
5	Explain the work process that you follow	Most of it comes from **my own experience and how I like to work and have worked.** So it's **not written down**, but the way I work and most of my colleagues work as well is that we **first identify the demands that are needed**. we look at early styling to see where we could have problems areas and inform people about that. **And then we look on the gap and flush demands.** We don't decide on values, we leave that do component owners. **We identify the demands that we need to look for**. Then I start talking to the different engineers or, say rule engineers, but component owners and see how all the parts built up, how are they fixed to each other? I imitate that discussion and try to nudge them towards something that works for me, like ohh you. You have a big part, but you only have fix things in a little little piece of it. No put fixes here and here for example, thats more stable. I try to influence them, because I know that in the end that will improve the gap and flush demands. Through those discussion we talk about **datum systems (reference systems) that I can use in my simulation model**. I also need tolerances, which are guess work in the beggining. **You can look at old projects for guidance. That's where the CM4D database comes in**. I also look at other functional requirements. And sometimes I find that and do a calculation and give that info to the component owners and sometimes other people come to me and ask for calculations. **So we have aestehtic calculations, gap and flush, and functional requirements.**	We are involved early in the process where we need to figure out how the new product will look. We have Digital Checks - DC3, 4, 5 and finally FDJ. About 6 months, one year and 1.5 years between the checks. We try to as early as possible from an ME and factory perspective give feedback o the construction. We have three key deliveries in the early phases: identifying areas where there is risk for clashing parts, working with final demands through out the DCs and delivering FDJ. Subsystems.	In running (production) we have a *control plan* which specifies what to measure, how many times etc. We follow a standard.	At the beginning we need the requirements based on **the control plan.** From the control plan we get all the measurement requirements, and based on the requirement we need to plan how to develop different equipment and software. We submit it to the management team and relsease afterward. Then the technical department and purchase department is supported to get from different suppliers. I need to **create the technical requirements of the software/equipment** to support the PD process. Then we follow up this project with the supplier, which includes the hardware and software. Then the euipment is installed and trained at our sites to **train our operators, technicans or others by programming them**. Then we support the IT department to develop the equipment further, for instance, the CM4D software, we **give feedback to IT**. Also, I need to **follow up with the part supplier** to submit the measurement. Sometimes the delivery from the supplier (DMO-files) is faulty, then I have to contact the supplier again, and then upload them to the system (CM4D) once again. Then I analyze the parts in CM4D. And thats what I do as a GEO engineer.
6	How do you work with requirements in your role?	*Answered in previous question*	*Answered in previous question*	We have a standard control plan that we follow. We measure the gap, flush, tolerances and send the feedback to the geometry engineers.	
7	What are your deliverables? a) In the form of documents?	I produce **tolerance sheets from the RD&T software**. These tolerance sheets could be called pre tolerance sheets, GDT documents, but here we call them tolerance sheets, which is basically a drawing, it's the basis for the drawing , the drawing maker which is not us should look at our tolerance sheet and take that info and put it in the drawing in the correct way. our document is just for discussion internally and also with the with the supplier later because the supplier needs to give feedback on that. **When we have the results, I put them in the gap plan - Gap and flush tracker in Excel**. It is desired to have weekly meetings where we discuss results with component owners and other people. Discuss the target, put guess numbers to have something to discuss. And if my calculation is larger than the target that we need to discuss, should we increase the target? Should we affect the tolerances? Either the tolerances directly or the reference systems to get the calculation lower. This is something that does not work well at Polestar, no one takes responsibilty for the targets. Everyone thinks its important but no one takes the step. This is my work and it loops, **I get feed back from the supplier and update the tolerance sheets**. Can be tricky to get the correct feedback from supplier. I update the calculations 20-30 times per project.	**Construction input, FDJ and subsystems**. In the form of PowerPoints that we use within the ME team. TcVis for input and our outputs are PowerPoints. Our team is kind of a **birdge between several teams within ME and to R&D.**	Contribution analysis. If we find issues, like a large contribution, we send that information to the supplier or other engineers. Suggest improvements.	
8	What requirement data do you need in order to perform your task?	Tolerances, reference system, gap and flush demands. Guess values.	*Answered in previous question*	*Answered in previous question*	
9	a) Who do you receive data from? (role and / or department) b) How do you receive the data (hand-over of information)?	a) Don't automatically recieve data from anyone directly. It's as the reference system which I **need to figure out together with the engineers**. And the guesswork of the tolerances as such you know, they're not completely guesses, they're based on something.	**Sebastian/Anderas provide us with the subsystems,** which tells us what possibilities there are for fulfilling the demands. The tolerance sheets are an input to the subsystems. When it comes to final demands and the gap plan, it is not exactly clear. Differs between interior and exterior. **We recieve the documents as PDFs through mail.** The requirement specification for prioritized parts and subcomponents is important as well, and single components with reference system + requirement spec., it is an "Engineering deliverable".	From ME. Sometimes from Quality team.	From the supplier. We do not have an automatic way of uploading the data into CM4D so they normally send it **via mail to me and I upload them manually.** Hopefully in the future this will be automated. We already have a deal with our local IT team where they promised to make this happen in the future by finding a solution that uploads the supplier data into CM4D automatically. For now, it is only a thought.
10	a) To whom do you provide data after completing your task? (role and / or department) b) How do you send the data (hand-over of information)?	a) we of course discussed a lot with the manufacturing engineering (Niklas' team). So Niklas team a little bit, but also other teams that we discussed with like how do we fixture set different things? So there's a lot of back and forth, a weekly with other departments. **We provide the the MP drawing**. We do the looping a lot like with the calculations and then at a certain point which is not set in Polar star, we start doing **the amp drawings** which define how the supplier should measure their part and that mismatch drawing we supply to me to the component owners which gives it to the supplier and we loop them as well if there's problems. But we also supply them to Niklas team because they need to load it into the the **CM4D software** so that when the supplier sends data to the database, it matches and it works together	Through PowerPoints, "One-voice to R&D".	To R&D and ME.	All the measurement data from the supplier and in-house equipment is **stored in the software CM4D**, you can review the data there. As I am in the same location as the GEO team, I just tell them to look at it. But if its faulty data-files (DMO) I will send emails to the suppliers. About the requirements, I share the information with our own team.
11	a) How would you describe the data flow in a geometry assurance process from start to finish? b) In what stage of this process do you place your own tasks and work?	It's **not really clearly defined where we have the deliveries exactly how it should look and what should be done** here and then who takes over. The concept-phase team are not very involved in manufacturing once they hand over the data, even if they help sometimes its the "factory" (manufacturing, Niklas' team) that drive the GA at this point in the process.	**DC3 --> DC4 --> DC5 --> FDJ.** Starts with R&D (Sebastian & Andreas), then ME (including some involvement with the factory), back to R&D with feedback. R&D then refines the data until the FDJ mark. During FDJ, we have final demands, drawings, subsystems etc and we "drop the pen". At this point it should be good to go.	-	We have a **developing plan of the geometry equipment**; in there you can follow the project name and activities. In that you can see which requirement and which equipment goes along. Also, stuff like installation, debugging, training operators and verification is included in the plan. It is based on the PD process here at Polestar.
12	How is feedback and iteration carried out in the data flow?	**We don't have a set process for it.** Send the tolerance sheets to the engineers, but if it concerns "kaross", then I also discuss it with Niklas team and I I **send it out in the mail, ask feedback.**	A lot of **"gut-feeling"**, once they ask for feedback, we give it. As Sebastian may have mentioned, no one asks them for deliverables. We at ME do have an understanding of how we would like it to work,	-	There is **no optical process to follow** up the different divisions of the suppliers. The R&D team hand over all the part and project requirements to ME team, our team. We then follow up by email, if its a too critical issue not resolved by us, we set up a common meeting where we can discuss the requirement. This is where we can give feedback to eachother, whether we need to push the suppliers or the R&D team.
13	How late in the process can changes be made to the requirements? a) How frequently does it happen?	I cannot answer that exactly. In other companies, they're probably rules for when it can change. I think **FDJ, it shouldn't change after that**. it can change if they in in production, when they measure the cars, they see that our measurements or read they are not fulfilled. But it looks good, so we change the requirement. **the requirements can change during the lifetime of the vehicle.**	I think you should be able to **as late as possible, if the demand change adds value to the product.** Even after you've "dropped the pen". But the **suppliers may not be able to keep up** etc. It also may be costly the later in the process it happens. **It is harder with physical components**, versus in DC3 where there are still just digital models.	It happens often. If we come across a design problem, we report back to R&D.	I do not have knowledge on this. a) Yes it happens, but I do not know how long time is spent on that. Normally **R&D can change it and give it to ME team again, but we need a "handshake" on this** to to that as it normally requires a lot of money and resources. Sometimes the management team or CEO needs to give inputs if its too critical.
14	How are new requirements verified later in the process?	**The ones who request the change contact us to see if it is a problem** because it could be that they have seen that it's not a problem on 20 cars, but we do 10.000 cars in our simulations. **it's usually goes to us, at least consults us and then they just update it. If there's a new requirement they contact us and say we don't have a demand here.** **Can we add it?** And then we do the **integer thing we we add it in the gap plan**, we do a calculation if we think it's no reasonable or and good to do that**, updated PKI and give that feedback to them.**	It should always be **R&D that verifies them**, because they are the part owners. On the other hand, if R&D wants a new demand, they consult with ME and the factory.	Mostly R&D. They change their simulations and create new document. Then we test the new requirement and we once again provide them with feedback.	Through meetings and discussion.
15	How are old versions of requirement data handled and stored? a) How often do you use them?	No, they are just overwritten.	I don't know. But there should be some kind of trackability through change management. Björn in our team works with change management.	-	We have a **setting in CM4D that shows the history** of what is changed and when to see cut-off time. But **not stored in another way.** a) The data from suppliers from previous things can show us how pre-assemblies or cars look or produced. Then we can **see how some final demands is affected by finding the root causes**. Probably that is from the production process in the A-, B- or C-shops. So, we can follow the tolerance chain to see which part is causing the problem, and then we can correct, update or use it as a learning. Then it can be verified on site.
16	How is perceived quality integrated in your work process?	Me and and component owners together and have officially said that we take a joint responsibilty for it. We don't have a PQ department. They are more experienced than the especially have the responsibility to know how much can a flush deviate before it starts look bad. we can figure out how much it will vary, but where is the break point? The ones you do the the styling surface, they are not experts in that either. **They see what looks good in CAD nominally,** but they can't visualize. So we try to find out where the gap flushed demands are, don't base it on data but just on how it looks. **A lot of guesswork.** I actually look at the numbers and I **refer to perceived quality in other companies** I've worked in in similar areas, like if we had a PQ they would complain about this or not. I do my calculations and see oh, this is a big value and I try to bring that up for discussion with everyone involved. the requirements I work with MPQ are all documented in the gap plan.	It is not really integrated in my work.	Not part of my work.	There is a special situation i Polestar, in different phases of a project we belong to different departments. In the launch phase we belong to ME, in the running phase we belong to the quality department. **So, besides the requirements we do not integrate PQ more than that.**

17	What kind of requirements related to PQ do you work with?	There are requirements in the gap plan. early in the project, we look at where we will have gap and flush demands. together with component owners, we we populate this gap plan like where should we have the demands? at least someone puts in targets, we can do it. They are put in somehow, but it's not a structured way like sometimes on the other people do it. Sometimes we do it after we talked with the engineers, but no one really owns them. **Gap, flush and alignment** are the most common requirements. It has been decided that we dont back up symmetry and parallelism demands in samulation at Polestar.	-	Gap-flush.	Yeah, the **gap and flush** but the **quality team is focusing on the feeling of these requirements**. But if the feeling is not good, they will want to change the tolerances of the gap and flush requirements going back to R&D. For instance if a tolerance is in range but the feeling of it in reality is not good, it needs to be changed.
	Problem-related questions				
18	What do you consider the most significant challenge with the requirement data management in your geometry assurance process?	That we **don't have a PQ department/person**. We l**ack proper deliveries** during the early phase. We **don't get tolerance feedback because the component owner doesn't prioritize it.**	Time-perspective. We have the knowledge, experience, tools in order to do the work but we lack in the time-perspecitve, when things are done etc.	I think our process is better than other companies. We follow the control plan, the designated process is good. I agree that the time-perspective is lacking. Everybody to talks about the same issue, but nobody can help us to resolve the issue.	
19	In what way can this be improved?	So the first one is either **higher peak person or a clearly defined from the higher ups.** Who is responsible for the demands? The second one is that we **should have more clear deliveries** and the teams we send things to should have **more clearly defined tasks in their process** that they recieve from us. in Cevt, for example, we had clearly staked out we need to provide this and then they have like 3 weeks to do a thing where we loop it and then it should be done.	I would like set deliverables and deadlines for each digital check. Also a clear definition of what do work with between each DC.	No suggestions.	Most of the challenges is from the **design changes, the project delay** and sometimes **invest limits** as the company wants to save money. Also, the **manual data input** from the supplier to CM4D is also ineffective. The manual part takes time. Also, that the **suppliers send faulty DMO-files** via mail and then I have to upload them to CM4D and investigate the problem myself - then I need to get in touch with them again so they can correct the issue I found and then have it sent to me again - and it happens too oflen.
20	Have you noticed other problems or less effective ways of handling the data in the process?	**The Excel file is messy and unstructured**. Anyone can go in and save it. Who is allowed to change what etc? **MP drawing are not connected to the part in TeamCenter**. Which can be a problem, Especially with revision management and so on, they have updated the part. OK, then we need to update the the MP drawing, the information of when it needs to be done, etc is lost.	**Lack of "hand-shakes"** in the workflow and processes. We often conduct the activities and have an agreement within the separate teams, but we **need "official" handshakes between the teams** and stakeholders. We need a **bigger agreement on how to do the work,** today each team has their own way.	-	
21	In what way can hand-overs of data be managed better and more efficiently?	**There should be a more strucutred way**. SharePoint could be used for handovers, not sure its the best way but it could. T**here should be folders** etc. Should be an **official agreement on how we do it**. So that could be more efficient that we have an agreement from both sides and also like a check from both sides that I somehow say I have now done this and then they say I have now taken this. **A way to track activites and updates in the workflow.**	We need smarter solutions, **scripts or macros, automated processes that manages the data**. Smart hand-over that manages the format of the data. It will be faster but mainly preserve data quality and accuracy.	-	By making it **automated**. It would save a lot of time. But in the case of faulty DMO-files I have no idea.
22	In what way is the process sensitive to variation and deviation?	So it's **very sensitive to to certain things.** If, if there's a **personal change, it would highly depend on who's left and who could teach the new person. Dependent on the individual doing the work.** if someone experienced from PE come in and take over what I do, it wouldn't be the end of the worl, but if they hire someone new there are **very little instructions of how to work, few "hard" deliveries.** **Requirement change - not very sensitive, its part of the work.** Minor problems is like project name changes just a number made a lot of links in SharePoint not work since it's done via links and who has access to what.	It is sensitive, very individual-based.	Presence of deviation and variation is a part of the process. The control plan is good and if you stick to it there won't be a lot of issues. Sometimes the standard might not be optimal	For now, I do not think a new engineer would manage to do the same job as the process is very **individual-based,** which is a weakness of the process. But it can be managed with support from Volvo, as they also work with the same softwares.
23	What are the potential consequences of the issues you brought up? For instance; - if the hand-over is not handled well - if documents are missing - changes are made - delays are occuring	**Lack of responisibility**. Someone comes in and says I'll wait until someone asks me for an update for this, which can work, but Then **they missed a lot of the discussions going on and a lot of the value for the program** I would say is lost. **Lack of clear deliveries can make the program suffer.**	Personnel change would likely imply a very different work process.	Delays.	Maybe that there will be delays or that the hand-overs will be mistreated.
24	What do you think works well in the process?	**the communication with the most department works**, especially manufacturing. So Niklas team, but also his sibling teams, you could say within manufacturing work really well. That improves like everything geometry related a lot, I think. We have set requirements and we do have that we should provide those calculations.	All departments work in harmony and we know what needs to be done in the end (final demands). We get there eventually, but is it the best way to go about it? There is room for improvement. The aspects where we actually do have specifications on what to do etc work well.	I think we follow a good process, everyone knows what to do.	We need a standard to limit the change and follop up and manage it from RDnT and supplier. Also, we need a team to manage all the change requirements Besides these aspects, it works well.
25	How can these aspects be integrated further?	**Someone need to have responisbility for the targets**, wether its a PQ person or someone who is dedicated. **more clear receiving dates** and a **handshake on on our deliveries.**	We need to gain a better understanding of the possibilities, what formats can be used for data management etc. Explore the possibilites.	-	
	Final comments	-	Consider robustness and variation early in the process.	-	-

E

Appendix E. The Transcription of the In-depth Interview

Appendix E presents the transcription of the semi-structured interview with a senior geometry engineer involved in the early phases of the geometry assurance process. The transcription is divided into *Questions* and *Answers from Interviewee* columns. The answers column does not contain the names of the interviewee for anonymity, but their company name and role are presented in the top row.

Transcription: In-Depth Interview

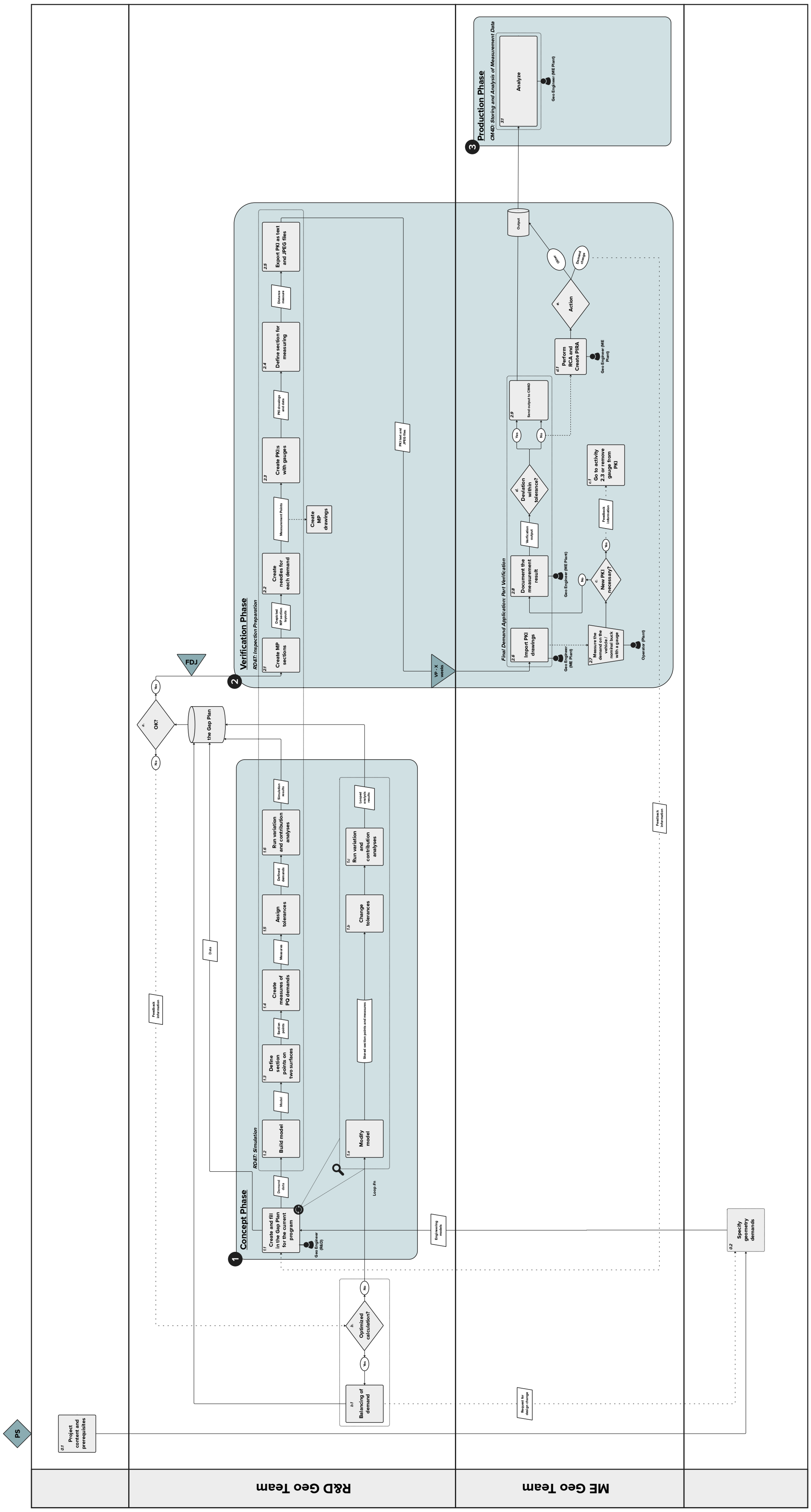
	Questions	Answers from interviewee
		Senior Engineer Geometry, Vehicle Integration (UK)
0	Is it okay to record the meeting? All material will be deleted by June 2024	Yes
1	What is your current role and how long have you been working as it?	To manage the Geometry team in R&D in the UK. I have been in this role since 2020, nearly 4 years. I have been doing this kind of work for probably 25 years. I am a manager of the team but I also work as an engineer within the team. I work with the modeling side as well as the management side.
2	What are your tasks and responsibilities? Explain the work process that you follow - How is a PS initiated? - Could you explain the figure for us?	Our task is to analyze the current vehicle designs in their many different phases from a dimensional variation point of view. So, specifically about part-to-part variation, it's important to know that two components cannot be identical geometrically, they are all different - and we work with how we manage those differences and achieve our dimensional objectives. So, the main operational activity is to take CAD information (CAD Geometry) and import it into our CAD environment which enables us to apply tolerances and datum strategies to the parts. Then, we can create fixtures where they are needed, which enables the assembly of those parts. Afterward, we replicate the assembly, subassembly, or full vehicle and that enables us to then virtually build 10.000 cars and measure each one very quickly. That enables us to assess the whole vehicle or the dimensional relation between two parts. - Ideally, we would like to start analyzing a design when it is complete, when we have all the information, the geometry is correct and all the tolerance information is at hand. But if we waited that long it would be too late to improve the design as it would be complete, so we have to start as early as possible. But that's not ideal but that's the only way it can be done. We wait until we have representative geometry, so we can make some meaningful analysis even though it is at a very basic level at the start of the program. That's based on experience from previous programs about when the best time is to start and it is really important that we talk to the engineers to get a good understanding of how mature their geometry is. If they know that it is going to change there is no point in us doing an in-depth analysis, so we may work at a different area and come back to that area when it has reached a certain level of maturity. It has happened in the past when we did a lot of analyses and work and then the design changed quite radically and we started again, which wastes our time. - The first box there - the engineering, CAD geometry and gap plan --> they are the inputs to our phase --> the green box - that would be all of the tolerance and material information, the CAD information is the actual CAD. We create the gap plan, which is the specification of the vehicle and that gets incorporated into our model. Those are the three things that get incorporated into our models. We also produce MP drawings, so if we are measuring a gap between a front and rear door, we specify where on the door it gets measured specifically. Then we produce a part drawing of the parts, that shows the measure points, which are at the same point even if they are different parts. The green phase is when we produce the actual models for analysis and development of drawings - the two outputs are the MP drawings and PKI drawings. Although we produce the MP drawings, the engineers/suppliers must approve what we have done and are aware of what we have done. Because this is the measurement they will receive. Further, the PKI and PKIV, that's similar to the MP drawings, it tells the operator who's measuring the vehicles and where they should be measured as it is specified exactly at the measurement point. Also, we may measure it at three places and that is specified exactly where they are. PKIV is part of the measurement of a vehicle, body or subassembly on a coordinate measuring machine, we create it in the measurement plant and give the information that is needed to the operators. The orange box is when the supplier starts producing the parts and uses the MP drawings to measure the parts, which tells us whether the part is acceptable or not - the supplier is the approver in this case but also the engineers. The engineers approve it often when they find it to have enough MP points. In the case of the PKI and PKIV, the assemblies are measured on the CMM, which is done by the ME Geo team. So, they get the same information and all of their results (both ME Geo team and supplier) feed their data into CM4D, from there we gather information and can fill in the gap plan more. It does not happen step-by-step, there is a lot of cycling and changing during the program but these are the "steps". We need to stay as up-to-date as possible when the design changes.
3	What are the tasks of the team you are responisble for?	Besides the gap plan and the tasks I explained in the previous question, we have the gap plan analysis where we assess the capability of the design to achieve the gap plan, which is basically a visual appearance target but there are also functional requirements that we cannot allow certain parts to be in contact with other parts due to various reasons, e.g noise, rattle, and tweak noises. So we got the functional requirements, it's all dimensional issues. And then we have ad-hoc study requests where potentially one of the engineers, let's say got three different processes for building his assembly and he wants to know which one is the best --> so we call that process choice, and then we can model each process and help him choose which one is the best. They can request any type of help regarding dimensional issues, they are always different but we like to help out as much as we can. To summarize, we have three main areas we work in: visual appearance, functional requirements, and adhoc design assistance.
*	*We know that your team also works with PQ, how do you feel about that and is it working well?*	I feel it should be separated from my team, we have had the responsibility since Polestar was founded as they do not have a PQ department. The role is kind of split between several different areas and our area is the main department working with the PQ, which we are happy to do as we are a team. But we are a dimensional team and we can't apologize for being dimensional so we will always look at things from a dimensional point of view. When we have decisions to make that will be our prime focus. Whereas a PQ person would look at it from all different points of view, not only dimensional but also appearance and doing different kinds of analysis. They would look at historical data and benchmark other vehicles and see where we are in the marketplace - a much more in-depth work. We help out with the dimensional side of the PQ, and I am constantly stressing to the company that we cannot be the only team working on PQ making decisions because we are just dimensional guys. We need other perspectives as well, so ideally one PQ team will be in place in the future which we can help as well.
4	How do you work with requirements in your role? How would you describe a final demand?	So, we start with what the customer would require as a target, a nominal value (gap or flush). We build our models and assess the capability of the design and then compare our capability values to the specification to see the differences - we try to improve those conditions. As we reduce the variation, we reduce our nominal and hopefully, we meet the target. The objective is to make that capability meet that requirement. Then we look at specifying the nominals in the gap plan, which can't be done without an accurate assessment of the variation - once we've set the nominals we do not want to change the CAD. At the same time, we have to make sure we are up to date with the process and we are not analyzing old data. The other big step is to make sure that the supplier is going to deliver the tolerances that we import into our models, obviously, its not gonna work if we put tolerances onto parts and assess the gap plan and assess that as green and be told by the supplier that they cant deliver those tolerances - so both sides need to agree what we need to achieve there. - There are two ways we can specify a demand, and I always ask this question and I have never really been given an answer. But one way to do it is to say that we analyzed the design, and let's just say we've got a 3mm gap anywhere on the vehicle, we analyzed design and there is +- or - 2 mm of variation in the design and we can't get it any lower so the demand target must be + or - 2 and that is based on capability. And the other way of defining what it needs to be is to say the customer will not accept + or - 2 mm, that's too big and it does not look very nice, the customer needs + or - 1 mm. So, we could still specify + or - 1 mm as the target, but our role would be to say that the design does not achieve that so we need to do some additional actions --> improve some tolerances, the process and maybe change the geometry. All of those imports and parameters can be changed to achieve a better target and that's how I would describe a final demand. So, ideally, what the customer will accept and what we are capable of delivering and may be some negotiations on that. Once it has been agreed, that has to be achieved. When I worked with companies in the past, both Germany and Japan, they were happy with having targets that they didn't achieve as they were trying to achieve them. But for us, the targets need to be reached, ideally.
5	What are the deliverables of the team that you are responsible for?	As mentioned before: MP drawings and PKI/PKIV drawings (along with text files).
6	How do you work with check-ins and gates within your team?	Not so much as other teams, we do not have any specific gateways but we feed into other areas, e.g. exterior and interior have gateways, and we deliver our status to their departments. They would have for example how much of the gap plan has been agreed as a percentage. By a certain gateway, they need to be at a certain percentage, so for each of those areas, we support our results. If there are any major dimensional issues in those areas including chassi --> we will feed our concerns to them and they will report them at the gateways. That is how it works at the moment and I feel it working quite well as it embeds our issues with other teams issues. In other companies I have worked within, the GEO team presents their delivery but it tends to be treated as a separate thing and not part of the bigger area so I prefer to do it as we do it at Polestar. The gateways are sort of 3 or 6 months apart depending on what type of gateway it is. In the four weeks before the gateway, we start gathering report information and review the status and make sure that everything is accurate on the day of the presentation.
7	How do you work with feedback and iteration? - With component owners? - With other teams?	We have some feedback loops but they are not particularly connected to the gateways. We have weekly meetings where issues and statues get raised, it's more of an ongoing process. If we feel like we do not get enough information or support we raise that.
8	In your opinion, what are the most evident challenges within your team? - Particularly when it comes to management of requirement data?	I think the most evident challenge is working with other teams and ensuring that they understand the data that we are providing. Often, we can provide a report with relevant data but it gets misunderstood. For example, they may ask how many cars are going to require rework from the statistical analysis that we have done but we cannot predict that. Because what we are doing is analyzing tolerance data by assuming that the distribution is normal and within a 3-sigma range bilaterally distributed. This does not happen in real life but it is a good way of predicting what is going to happen during a lifetime of a car. The challenge is to present the results and information. If we design a really good car and we employ bad suppliers and the parts are no good, the car will not be good. So our job is to make sure that the design is good and going to work and make sure the parts and fixtures are tolerance and capable. All of the other things that could happen in real life we do not account for on a computer. It is a matter of explaining, the biggest challenge is explaining the results and providing them to make people understand (lack of common understanding)
9	What are some issues that can impair the data quality?	An example, when we have said that we have measured some vehicles, and someone will ask we have measured vehicles can we make an analysis of how well we are doing and we have only measured 10 vehicles, I have to say that it is too few as it is not representative of what we are capable. So the use of measure data is one, as we constantly get tasked to use measure data that is not a good fit for the purpose. It's interesting and an indication of what we have done but not an indication of what the future is gonna hold, so that's one. The general issue of using tolerances and if I say there is a mean shift, no matter how many measurements we take we never really gonna have a mean that is centered on the nominal. So, we got a lot of issues with suppliers particularly with plastic and larger parts, where the supplier insists on having a large tolerance. For example, + or - 3mm on the length of a plastic part, but what they are saying is that the parts are not gonna vary a great deal but they will be mean shifted in that 3 mm so we need a 3mm tolerance. This is a constant big issue, in the conversation between suppliers and engineers.
10	Are there any time-consuming bottlenecks present in the process?	We always get the question from a designer: "here is the geometry, can yo get back to me tomorrow?" But what they do not know is that, that work is taking three weeks so our team is the natural bottleneck. As we are at the end of the PD process, we have all the information from previous stages. So we always try to do the work upfront. But putting the tolerances into the model takes time and there is no quick time of doing it and it can't be rushed.

11	What are the greatest strengths within your team?	The greatest strength within my team is their knowledge and experience, I am fortunate to have people that has been involved in a lot of vehicle integration programs with hands on experience. And obviously the skill and experience within RD&T is a strength.
*	*Do you think it could be negative that the results rely on the expertise of the team?*	We are very dependent on the skills of our team. The reality is that we would like to document our processes for future engineers but we do not have much time for that as the programs start even before the other is ended. We have some documentation amongst ourselves, but it is not enough. There is a lot of information carried with the engineers, which would be lost if the engineer left the team.
	Discuss interview results - challenges	
12	Do you agree with these statements?	I agree with all of those common findings. My first thought when I went back to my first months at Polestar, we were like a startup company and it impressed me that we are not like Volvo - we do not have the same resources and people to operate like them - so we need to be very lean and quick, but also work agile and work with our processes. There was very little management structure and focus on the results. You were left alone to work towards the objective. Over time it quickly became evident that we could not work without gateways, absences of various departments, without trackability. Agreements were made on trust, people would agree on something verbally and thats not the way a business should go. We need to get more professionals, we are not there yet but we want to do better. We still do not have official hand-shakes, most things are still based on trust. The idea of the gateway is to make sure that the design is at a certain stage before going further, but in reality, we carry on which is not a good way of working as we do not have a good gateway discipline.
13	What do you think is the reason behind this?	We need a PQ department, the only obstacle there is the desire and resources to create one. It needs to work with every other department, which is not as easy as it sounds, they must operate positively. The issue with no proper deliveries, for me, this goes back to the gateway discipline, we constantly get asked to deliver to the people that has not provided us with the necessary inputs, and they go like: "we haven't finished the design but can you still start analyzing?" It ends up pretty messy, which makes our deliveries time-consuming and not a good way of working, I would like more discipline in that. We are now trying to convert Volvo standards to Polestar standards, which will hopefully change the culture. The culture at Polestar is not used to standards but it needs a change. For example, if you could not work on your own and needed a process then you were not going to make it. Using own initiative was the culture but it has to be changed and encourage people to standardize the work process. Personally, I think a standardized process is needed with room for own initiatives, if there is a scale I would say the ratio would be 90/10 %. Without processes it is quite complex to work and complete the tasks, so we need the processes to work towards, now that the company is growing. It is going to be very difficult to implement as there will be resistance from the teams.
	Discuss interview results - imporvements	
14	Why do you think these improvements would or would not be feasible?	I think they would be feasible. The storage and recording of the changes is the first thing people stop doing when they are busy, so automating that would help the engineer and save a lot of time. We also spend a lot of time defining and recording the work we do, but it never is being used afterward. The data in my team is not stored and traceable, so it is inefficient so an improvement would be good. Often, we create our own excels if we need to store something.
15	Do you have any other possible improvements in mind?	The question of interpersonal agreements, no official agreements on deliverables and so on, still exists. But that is not a good way of working, we need a more professional way of working and maybe sign the agreement and show the approval. We need to make sure that there is accountability.
*** Questions generated during the interview**		

F

Appendix F. The Process and Data Flow Diagram

Appendix F presents the process and data flow diagram of the geometry assurance process, which is divided into three phases: concept, verification, and production. These phases are visualized as blue boxes containing their respective activities. Additionally, the diagram is organized into separate rows based on the responsible team for each activity or phase.


R&D Geo Team
ME Geo Team
Concept Phase
Verification Phase
Production Phase
FDJ
PS
the Gap Plan
OK?
Balancing of demand
Optimized calculation?
Project content and prerequisites
Specify geometry demands
Create and fill in the Gap Plan for the current program
Build model
Define section points on two surfaces
Create measures of PQ demands
Assign tolerances
Run variation and contribution analyses
Modify model
Change tolerances
Create MP sections
Create needles for each demand
Create PKIs with gauges
Define section for measuring
Export PKI as text and JPEG files
Import PKI drawings
Document the measurement result
Deviation within tolerance?
New PKI necessary?
Perform RCA and Create PIRA
Action
Analyze

G

Appendix G. The Transcription of the Interviews with Engineers from Competing Companies

Appendix G presents the transcription of two interviews with engineers from competing companies specializing in the PQ aspect of the geometry assurance process. The appendix is divided into *Questions* and *Answers from Interviewees* columns, each containing subcolumns. The answers column is further divided into two subcolumns, each representing the transcribed answers from one interviewee. The names of the interviewees are not presented due to anonymity, but their their company names and interview dates, are presented in the top row of each subcolumn.

G. Appendix G. The Transcription of the Interviews with Engineers from Competing Companies

Transcription: Interviews with Engineers from Competing Companies (PQ)			
Questions		**Answers from interviewees**	
		Principal Engineer, PQ at VCC (20/2-24) - translated from Swedish	*Head of Project Quality and Vehicle Validation, PQ at CEVT/ZEEKR (28/2-24) - translated from Swedish*
0	Is it okay to record your answers? All material will be deleted by June 2024.	Yes	Yes
1	What is your current role and how long have you been working as it?	Currently, I am working as a **Principal Engineer in PQ Geometry at Volvo Cars**. There are other PQ departments like material and illumination but I am at geometry. I've had a few different roles but I have been in Volvo Cars' PQ department for 12 years.	I'm a manager, **head of project quality and vehicle validation**, I've had that role for about a year. It is about taking care of quality project managers (kvalitetsprojektledare) and testers of cars in the final phase to see what the customer wants.
2	Have you had other roles related to geometry assurance/PQ?	Before my current role, I did my doctoral thesis and worked as a researcher within Geometry Assurance and PQ at Chalmers University of Technology.	My first role after Chalmers started at PQ at **Volvo as attribute leade**r for PQ Geometry where I worked with gap and flush, setting requirements, benchmarking and following up in projects etc. Afterward, I started at CEVT in 2015 to build up PQ concepts, just at the stage when **CEVT** didn't have many in PQ. And then I became head of PQ and dimensional engineering (geometrisäkring). Now I don't have PQ with me, because of how we work with ZEEKR at CEVT - we have all the development in China, they are the ones who work with PQ and requirements. But in my role as quality, we do follow up on PQ to get the whole picture of the car - to see what looks good and bad, as we have the responsibility to check it.
3	How would you describe "Percieved Quality" and its connection to geometry assurance? a) Why is it important to consider PQ when developing cars?	It is how the customer experiences the product quality. It can be divided in many different ways, as seen in different companies, but the flush and gap are the requirements affecting the customer's experience firsthand. a) It is because the customer wants to buy a product that feels well-built and symbolizes the technology behind it. For example, if a customer is buying an autonomous car, they would want to feel safe with the product and trust the quality of it, which is where PQ comes in.	For me, PQ is - if you go to a car dealership, **it's about the feeling when you get in a car,** because a lot of people don't think about gaps and flushes like us. So its about first impressions, attention to detail and craftmanship. It should feel well thought out, well-built. a) The customer today thinks it's more important, as it's not just a transport solution today. You should feel comfortable and good in the car.
*	Do you see any problem with not having a PQ department?	It depends on the work process; working with geometry assurance is the essential part. Then it is clear that a large organization like Volvo Cars has multiple "egenskapsområden" (property areas) for the car, and PQ is one of them. You work in a certain format; you have certain reports so that the project management keeps track of how the car is performing from various perspectives, ensuring a proper balance between different property areas. If you have different individuals working on geometric assurance development and providing feedback on design, the only issue I can think of is not having a holistic view of the car and being able to maintain it. At Volvo, PQ also includes appearance, "detaljutförande" (detailing), such as taking care of visible screws and weld points that you do not want to show. It's good to have it along with geometry assurance because there may be a need to hide things both nominally and non-nominally. So, let's say you have a fairly large spread, and you have a weld point peeking out, then you can inspect it simultaneously and account for geometric variations. I don't know how this works without it at Polestar but these are the good sides of having a department. And I also believe it works in different ways in different organizations, as long as it works well. Then in Volvo Cars, PQ does the visualization and not R&D, but that is possible to use in the R&D department as the decision basis as there is no PQ department in the organization (Polestar).	-
4	What are your tasks and responsibilities?	I work as a **Principal Engineer,** which can be seen as a senior developer at Volvo Cars. I also have the role of **attribute leader.** We have a large group of attribute managers and a couple of visualizers, who take care of data analyses. As an attribute leader, you are responsible for securing the property in a project. It is necessary to ensure that, both in the long term and in the project, the necessary solutions are brought in to provide the conditions. For my part, I work very early (early stage) and it is quite complex as we have quite a few solutions in the platform. A lot of investigation is done through advanced engineering before the project starts and then comes design. Then you know what to optimize against. For example, mega-casting comes first and then design. Of course, when design comes, you know how it should look and you have to optimize it. We collaborate with R&D, they are responsible for optimizing the systems and solutions. We are very dependent on them. When the design comes, we try to influence the split-line concept itself, can be quite simple things, for example, that the hatch should be able to be opened. We work on the whole car and then it is divided into the next department: exterior and interior. It is important in our department to have an overview of the entire car. To conclude, I do: influence the design, systems and solutions; give feedback to design; and make sure the car we build is good enough (as defined by competitors).	I'm a manager so my responsibility is to take care of my staff, then I also work in projects. What we do within the group is to ensure the quality of the projects, ensuring that we have the right deliveries for all parts of a car project from the very beginning. Those who work with business quality look at whether the financial targets are met, but even if we have the right content, if it's the right car, is there a plan, etc. We also work with FMEA, follows up projects and support R&D - mainly helps them with risk management etc. In different stages of the project, we do have design reviews as well, which means that we follow the status of the attributes of the project. Next step in my role is the validation - it is in that stage we drive the cars and test them, both in winter- and summerexpeditions. We also do something called QRTs (Quality Reliability Tests) on a test track we have in Europe. There, we drive the cars up to 40000 km to correspond to the customer's first 5 years with the car - this is done to be able to make analyzes and make calculations. In the overall process, I would say that we are involved from start to finish.
5	Explain the work process that you follow	There are many separate documents and processes at the same time. You start in an early gate "architecture kickoff", architectural work. Then you come to another gate called "PSI", then the project begins. What happens then is that you get an order - so we always work from an order and we shouldn't over-spec, maybe 30-35 demands at most. You see which ones you should be good and competitive at. Then the requirements are set, we do not set flush and gap requirements then but when the design is mature. Soon after, we get the first design release. Then you work with parallel tracks and only surfaces. Our task then is to give feedback on this. Then we have a gate called "DSM" and then we have a fairly mature underlay. Then we set flush/gap requirements, in my role, I usually hand it over. Usually, you behave as if the requirements control the solution you develop, project development methodology (requirements-driven product development). But it doesn't have to be like that, for example, if you have a new panel and you set a requirement of 2mm but 4mm looks better. Afterward, you make a calculation and see if the systems meet the requirements, eg RD&T. The next gate is the PC, then the requirements must be balanced. Then you get to the industrialization phase, detailed construction, and then we know the exact cuts and exact data from the supplier. Then you come to a gate called FDJ, which is when you drop the pen and requirements are established. Then it continues to physical construction and then we get a set of fulfilled/not fulfilled requirements, then you see that everything is not working. Then we rebalance the requirements through a project decision or adjustment. You have less space in this phase.	
*	Do you have clear deadlines for deliveries etc?	Yes, through our gates. We will do technical input on design releases, reports on where we stand at each gate, in the visualization phase we also get non-surface models and then we do evaluations on them as well.	-
6	How do you work with requirements in your role? a) What type of demands? b) Where do you store and document them? c) How is old versions of requirement data handled and stored? d) Do you find storing old requirement data important/useful?	a) Focusing on geometry, it is flush, gap, alignment and parallelism. b) Well, we have the requirements in RDnT and follow-up in SharePoint but no PDM system. Used as a basis for Power BI so you can filter and track what is green and red. But only until FDJ and after that SharePoint is not updated. But GAE also uses a system called Vira, then they check splits and tracks them. Then we have CM4D which is used in production. c) We keep the original requirements, the reason is that there are always discussions that change the requirements and finally you see how much of a jump was made from the original requirement. They are stored in RDnT or they are stored in SharePoint. However, you can check the history yourself, we place a lot of demands on handling requirements. We also store requirements from old car models, but I don't know how often it is used. But of course, old platforms are a good basis and reference.	a) It's usually R&D that sets the requirements, we just follow the process such as for the flush and gaps. b) There are lots of different systems we use to store and manage requirements, for example we have SystemWeaver for requirements management and work with the follow-up there. In addition, we have a system for monitoring the status of all areas of quality assurance. c) We do, it works pretty well. d) It is useful as it can be used as a reference if necessary.
7	What software and systems do you use during the process? a) For activities related to GA? b) For storing requirement data?	As said before; RDnT, SharePoint, Vira, CM4D but also presentations	RDnT, TeamCenter, VRED, SystemWeaver for requirement data.
8	How do you define the requirements related to PQ? What is it based on? a) Explain the process from start to end (briefly)	The idea is that it should be based on benchmarks, we only have access to competitors' cars, so you can't say this should be it. But in fairly basic parts you can tell right away what it should be. What we need to do is take the right to deduce. How it looks also plays a big role, in what the customer expects in the back of their mind. What does it look like with transparency? Does it get light? Do you see edges? The requirements for the entire car are good enough, but then we at Volvo Cars focus on certain requirements we want to be better at and focus more on that, to stand out from our competitors.	It's based on PAP - product attribute profile. We recieve an order for what kind of car we want to design and in what "category" of competing brands. Conduct benchmarking of competing brands and based on a visual judgement set demands that look good in the competing cars. Our documents are called DTS, which contains mainly visual judgements. A lot of our employees have experience from other companies that they utilize in our process.
9	In what way is the process sensitive to variation and deviation?	Rarely able to train someone, it's an open task with own initiative. It's important to leave a paper trail, weekly. My colleagues have to keep track of what I've done. Then we also have different types of documentation in the different problem areas, what have I said and what do we think as a group? Communication is important as we have offices in different locations. Could be a problem with people not valuing documentation, but in general SharePoint is pretty safe. More that it is the human factor. The problem is that you use two systems: RDnT and SharePoint and sit and fill in them parallelly. Another problem is that different models are built in different locations due to sourcing, then we have to be extra careful with FDJ as we have two requirement documents, but they have different problems with different requirements from their suppliers. Problems with keeping order in late-phase requirements are common. Having different factories makes the system robust but it comes with problems, the data management takes a bit of a hit.	It is affected negatively. In a perfect case we would not have any variations in our process. In case of a personnel change, we aim to always keep a common agreement and mindset in our team. It is fairly individual based, but if someone new starts they would be trained. We lack a clear standard. We have some deviations in perspectives here in Europe and China, som differences in approaches.
10	How is feedback and iteration carried out in the data flow?	As I said before, it is very iterative and everything loops back to eachother.	We perform a lot of looping, We send feedback to the GA engineers, they do calculations with what has been constructed. A lot of discussions and trade-offs with other teams, like material. In a project, we often have check ins once a week with other teams. We have a shared PowerPoint with requirement data that both the PQ team and GA team have access to. For tracking changes.
11	What do you think works well in the process in terms of data- and informationflow?	We manage to document in a good way, so we have the information we need, but then the problem is that it takes a long time. There may be ambiguities but it is very traceable. For example, the standardization of what is to be filled in. The traceability with the time aspect is good, but what goes worse is by whom and why. It can be de-prioritized due to workload, but forcing people to write more can be a problem. Each line in Excel is an input, there should not be columns that are not used, but only the most important which can be left out. But it still works well, the only problem is the double update.	The teamwork and information exchange works well between the PQ and GA team. Also manufacturing.

12	Anything you want to add that we could have missed to ask?	Choice of benchmark data, so it can be interesting to produce it. Say you have a system where you can produce all the requirements on the back hood, but the problem is all the deviations. Overslam - that the hood and hatch slam down so it springs and it pies the lamp, so you need a margin - in such a game, dimensioning is important. If you have only one database, it can be confusing to determine what is being referred to – is it the same relationship? This ambiguity could lead to mixed data. To address this, for PQ to precisely locate where the specification is, RDnT can be rechecked. Ensuring consistency in requirement numbers, standardization, and searchability is crucial. For instance, if a screen should be named consistently, searching in old documents may yield different names. In such cases, it might not correspond to the same item when reviewing the requirements. Therefore, it is a factor that needs consideration. Meetings with safety, aerodynamics and PQ (etc) are done iteratively. Our work is about visual perception and also collaboration with other departments, so they can bring in the technical aspects.	A few years back, we split the PQ team which I think caused us to lose some of the entirety. Its a good idea to work closely early in the process, learn a lot from the feedback and iteration. There is a greater chance to impact early in the process. The later, the more expensive and difficult. In order to be effective, we need a clear requirement specification early. Sometimes it is beneficial to strictly follow a standard and sometimes it is not. It has occured that we had to change a demand even after FDJ, which Volvo for instance may not have done since they have a mor strict standard. This may also slow down their process. In order to establish a PQ department at Polestar, several aspects need to be considered and not only geometry.

Questions generated during the interview with Karin Nordvall

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