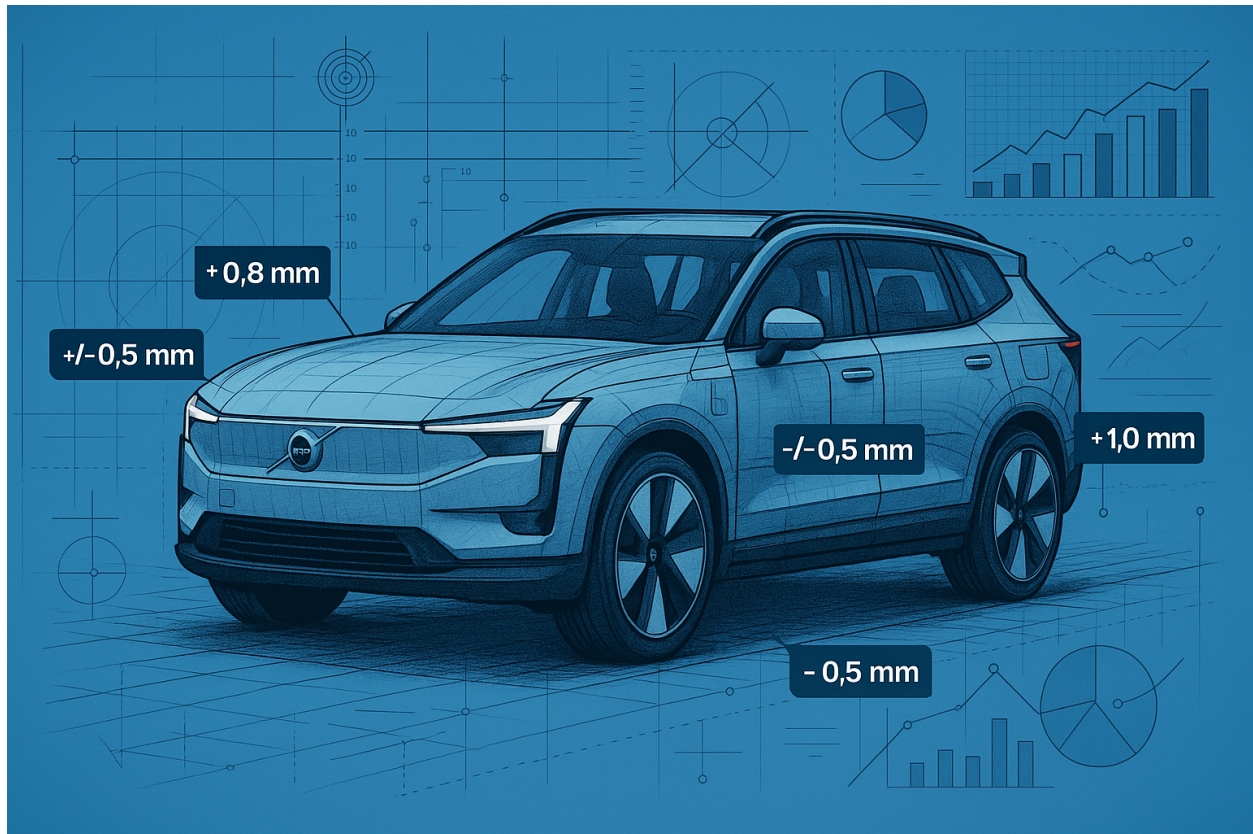




CHALMERS
UNIVERSITY OF TECHNOLOGY



Tolerance Simulation Optimization with Data Analysis

Master Thesis in Product Development

Midhun Sai Gadiparthi

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
www.chalmers.se

MASTER'S THESIS 2025

Tolerance Simulation Optimization with Data Analysis

Midhun Sai Gadiparthi



CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Industrial and Materials Science
Product Development

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025

Tolerance Simulation Optimization with Data Analysis
Midhun Sai Gadiparthi

© Midhun Sai Gadiparthi, 2025, midhun@chalmers.se

Examiner & Supervisor: Kristina Wärmefjord, Chalmers University of Technology
Industrial Supervisor: Jie Shao, Volvo Cars, Geometry Assurance Painted Body VCC

Master's Thesis 2025
Department of Industrial and Materials Science
Product Development
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden Telephone +46 31 772 1000

Cover: Drawing of a Volvo Car with tolerances and data analysis, AI-generated image [1].

Typeset in L^AT_EX
Gothenburg, Sweden 2025

Tolerance Simulation Optimization with Data Analysis
Midhun Sai Gadiparthi
Department of Industrial and Materials Science
Chalmers University of Technology

Abstract

This thesis study primarily focuses on simulation chain accuracy through data-driven optimization techniques within the BIW (Body In White) assembly. Geometry assurance plays an important role in maintaining the quality throughout the product's lifecycle by managing the deviations that originate from manufacturing and assembly processes. In complex assembly scenarios, especially within BIW Assembly that involves mixed materials and varying structural rigidity, the simulation accuracy becomes challenging, and it requires a better understanding of existing models. The primary objective is to refine the simulation models that predict geometric variations to enhance the predictive capability. To achieve the objective, a detailed correlation study has been conducted, analyzing and comparing the real-world measurement data with rigid and non-rigid simulation models, assessing the effects, like process adjustments.

The comparison study between the production data and tolerance simulation model data is used to derive root cause analysis within each sub-assembly. Based on this study, improvements were made within existing rigid simulation models and suggested optimized simulation guidelines. This research aspires to find the major contributors to the geometrical variations within the BIW Upper body assembly and also to bridge the gap between simulation models and real-world data, improving the robustness within the rigid body simulation.

Keywords: Geometry Assurance, Rigid & Non-rigid Simulation model, Process Adjustments, Body In White, Optimized Model.

Acknowledgements

I am deeply grateful to my supervisor at Volvo Cars, Jie Shao, for the constant support, insightful guidance, and consistent availability throughout this thesis journey. Your mentorship played a pivotal role in shaping this work, and your encouragement at every step ensured that I never felt alone in this process.

I would also like to express my deepest gratitude to my manager and principal engineer at Volvo Cars, Antonio D'Elia and Josefin Hansen, for giving me the opportunity to join the team as a summer intern and for entrusting me with the responsibility to carry out the thesis work as well. Your encouragement and continuous support have been truly motivating throughout this journey. I would also like to extend my appreciation to all the interviewees who took the time to share their knowledge and experience, and your insights were valuable to the success of this study.

Also, my heartfelt thanks go to my examiner, Kristina Wärmefjord, for the thoughtful feedback, guidance, and continued support during this project. Your expertise and commitment have been instrumental in enhancing the clarity and quality of this thesis.

Finally, I wish to express my deepest gratitude to my family for their unconditional love, encouragement, and belief in me.

Midhun Sai Gadiparthi, Gothenburg, June 2025

List of Acronyms

The list of acronyms that are used in this thesis are listed below:

GA	Geometry Assurance
BIW	Body In White
CAT	Computer Aided Tolerancing
CAD	Computer Aided Design
RD&T	Robust Design & Tolerancing
CM4D	Computer Measurement Machine Management Mechanism Data
R&D	Research & Development
FEA	Finite Element Analysis
DRM	Design Research Methodology
GD&T	Geometric Dimensioning & Tolerancing
RSS	Root Sum Squares
MC	Monte Carlo
PQ	Perceived Quality
PMI	Product Manufacturing Information
CMM	Coordinate Measuring Machine
RCA	Root Cause Analysis
BSC	Body Side Complete
BSI	Body Side Inner
BSO	Body Side Outer
MP	Measurement Point
PA	Pre Assembly

Contents

List of Acronyms	ix
Nomenclature	xi
List of Figures	xiii
1 Introduction	2
1.1 Background	3
1.2 Purpose & Aim	4
1.3 Research Questions	4
1.4 Limitations	5
1.5 Summer Work Continuation	5
1.6 Body in White Assembly	5
1.7 Computer Aided Tolerancing	6
1.8 Geometrical Variations	6
2 Theory	8
2.1 Geometry Assurance	8
2.1.1 Robust Design	8
2.1.2 Locating Schemes	9
2.2 Tolerance Management	10
2.2.1 Tolerance Allocation	10
2.2.2 Tolerance Analysis	10
2.3 Tolerance Simulation Methods	12
2.3.1 Rigid Simulation Model	12
2.3.2 Non-rigid Simulation Model	13
2.3.2.1 Virtual Assembly	13
2.3.2.2 Scanned part setup	14
2.4 RD&T	15
2.5 Perceived Quality	15
2.6 Process Statistical Parameters	16
2.6.1 Tolerance Range	16
2.6.2 Sigma	17
2.6.3 Process Capability (Cp)	17
2.7 Measurement data	17
3 Methods	19

3.1	Methodology	19
3.1.1	Qualitative Analysis	19
3.1.1.1	Literature study	20
3.1.1.2	Initial Interviews	20
3.1.1.3	Simulation Models Setup	21
3.1.1.4	Body Side CPL Assembly	22
3.1.1.5	Simulation & Measurement Data Setup	23
3.1.2	Quantitative Comparision	24
3.1.2.1	Dataset Preparation	24
3.1.2.2	Dataset Visualization	25
3.1.2.3	Correlation Study	25
3.1.2.4	In-depth Interviews	26
3.1.3	Final Optimization	26
3.1.3.1	Root Cause Analysis	26
3.1.3.2	Final Optimized Model	27
3.1.3.3	Simulation Guidelines	27
4	Results	29
4.1	Initial Interviews	29
4.2	Rigid simulation Model	30
4.2.1	Improvement 1 - Review Tolerances & Cp Values	31
4.2.2	Improvement 2 - Duplicated Tolerances	32
4.2.3	Improvement 3 - Update Alternative Assembly	33
4.2.4	Improvement 4 - Part Tolerance Cp Values	33
4.3	Compliant Model results	36
4.3.1	Interval Plot with Multiple Mean Shift	37
4.4	In-depth Interviews	43
4.5	Root cause Analysis	44
4.5.1	PA RR Qtr	44
4.5.2	PA Drain Channel	45
4.5.3	PA Spider	46
4.5.4	PA T	47
4.5.5	Unside Ext	47
4.6	Optimization	48
4.6.1	Rigid Simulation Model Optimization	48
4.6.2	Simulation Guidelines	50
4.7	Fish Bone Diagram showing key Contributors	51
5	Discussion	53
5.1	Research Questions	54
5.1.1	RQ-1	54
5.1.2	RQ-2	54
6	Conclusion	56
	References	57

A Appendix	I
A.1 Initial Interview Questions	II
A.2 Interactive Plot created in PowerBI	III
A.3 Interval Plot with multiple mean shift	IV
A.4 Mean Shift Comparision	V
A.5 Fishbone Diagram	VI

List of Figures

1.1	Geometry Assurance Loop [2]	3
1.2	BIW Assembly of Volvo Cars XC90 [9]	6
2.1	P-Diagram showing the factors [13]	9
2.2	Rigid and non-rigid locating schemes [2]	9
2.3	Normal or Guassian statistical distribution curve [15]	11
2.4	Monte Carlo simulation workflow	12
2.5	Virtual Assembly Modelling Setup [22]	14
2.6	Scanned Part Setup [22]	15
2.7	Images showing split lines of an Volvo EX30 Car	16
3.1	Body Side Complete Assembly	22
3.2	BSC Assembly Flowchart	23
3.3	Measurement point data in CM4D highlighting outliers. Confidential information covered.	25
4.1	Scatter plot comparison between rigid simulation data and measurement data (old)	30
4.2	Scatter plot Comparison after tolerance & Cp value review and removing duplicated tolerances	32
4.3	Scatter plot after updating the alternative assembly	33
4.4	Single Part Cp Value with consistent data	35
4.5	Scatter plot after Single part Cp Value update	36
4.6	Interval Plot with multiple mean shift	38
4.7	Legend of the Interval Plot	38
4.8	Mean Shift of Compliant Model & TT Series Production	39
4.9	Mean Shift of Running Production & TT Series Production	40
4.10	Y Direction Measurement points Interval plot	41
4.11	Z Direction Measurement points Interval plot	42
4.12	X Direction Measurement points Interval plot	43
4.13	Illustrating the process adjustment in PA RR Qtr	45
4.14	Illustrating the process adjustment in PA Drain Channel	46
4.15	Illustrating the clamp locator shift in PA Spider	47
4.16	Illustration of variations on PA T	47
4.17	Illustrating the lack of clamps on Uniside Ext	48
4.18	Scatter plot after rigid model optimization	49
4.19	Fishbone Diagram showing the key contributors to geometrical variations	52

1

Introduction

Geometry assurance is an area that has been extensively studied over the years. Following the Second World War, Japanese quality saw significant improvement in manufacturing products, which also influenced advancements in Western countries during the 1980s. A robust design concept is widely used as it remains resilient against variations, and Taguchi originally introduced this concept in the context of quality improvement. Today, these robust design principles are widely followed and implemented across manufacturing industries, particularly in the automotive sector [2].

Volvo Cars is a Swedish car manufacturer founded in 1927 and is one of the most well-known brands in the automotive industry around the world [3]. Volvo Cars integrates geometry assurance as a critical element of its Research and development to ensure high product quality and dimensional accuracy. Geometry assurance engineers at Volvo use a simulation tool - RD&T (Robust Dimensioning & Tolerancing), which is a tolerance analysis software to predict the geometrical variations within the BIW Assembly process.

In the automotive industry, products are inevitably different from nominal designs because of the influence of various factors in the manufacturing and assembly process. Deviations within the single part level may cause problems in the final assembly, thereby increasing the overall cost of the product. So, tolerance simulation is done in the early stages of product development to ensure a robust assembly process. In the BIW assembly process, tolerances are crucial in fulfilling both technical and functional requirements. Properly defined tolerances help to ensure the product's functionality, but also significantly reduce the manufacturing costs of an automobile. As a result, tolerance analysis has become a crucial part of the product development process. It is widely acknowledged that optimizing tolerances and performing tolerance stack-up analysis during the early design stages will have a greater impact on cost efficiency than making adjustments in production [4].

In the development phase, GA(Geometry Assurance) will have a set of practices focused on controlling and minimizing the effects of geometrical variations throughout the product development and manufacturing process. It plays a crucial role in ensuring the final product meets the demands. These activities span various stages of product realization, starting from the concept phase, where initial product and production ideas are developed and evaluated. Different design alternatives are explored and optimized at this stage to ensure they are robust enough to handle expected manufacturing variations. Developing an early tolerance simulation model and virtual testing of that

model based on available production data helps to make informed design decisions, which also includes the allocation of tolerances. As the process moves to the verification or pre-production phase, the focus shifts to physical testing and validation for both the product and assembly process. This primarily helps identify potential issues before production begins. Preparation for inspection processes, such as programming measurement systems and establishing inspection routines, will be included in this phase. During the production phase, all adjustments to the production process are finalized, and the product enters full-scale manufacturing [2]. This geometry assurance loop is adapted below in Fig. 1.1. Together, these will help reduce geometrical variations in the early stages of development. So, the GA includes key activities such as virtual simulations, robust analysis, and assembly verification, which enable engineers to predict and control how part variations will act in final assembly. Ultimately, geometry assurance helps balance product performance and aesthetic requirements, contributing to achieving significant quality in production.

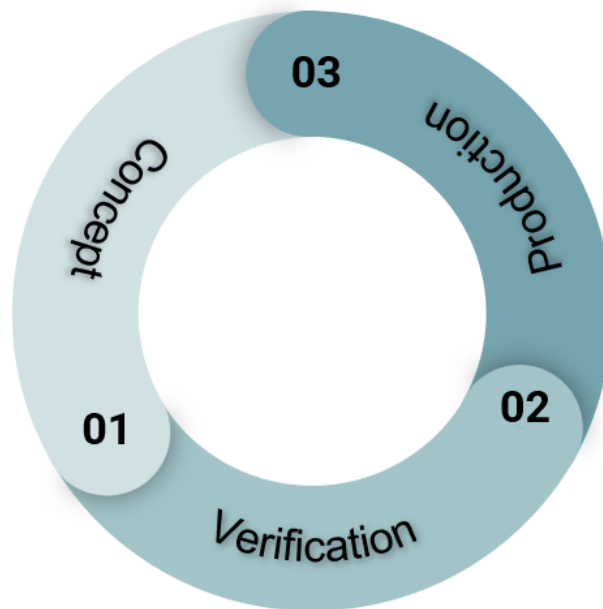


Figure 1.1: Geometry Assurance Loop [2]

1.1 Background

Today's rapidly evolving global market has industries competing with each other to deliver automobiles with precision, high quality, and cost-effectively faster than ever before. Manufacturing processes are becoming more complex, interconnected, and automated, driven by digitalization and increasing customer expectations. This transformation heavily relies on simulation, optimization, and data-driven decisions to stay competitive and innovative in the market [5]. So, most companies today are following an effective digital geometry assurance process to reduce cost and achieve higher precision [6].

Analyzing variation and tolerance outcomes through efficient simulation methods creates the ideal conditions for optimizing simulation chain calculations and meeting product requirements [7]. Tolerances define the acceptable range of variation for a specific dimension or feature. This variation and other influencing factors impact the overall tolerance variation in an assembled product. Tolerances are crucial for meeting assembly requirements and ensuring the final product meets functional and aesthetic standards [8].

GA describes the focus on managing and minimizing the effects of geometrical deviations on product quality throughout the product's life cycle. These deviations stem from inevitable manufacturing, assembly, and joining process variations. The work of geometry assurance begins in the conceptual phase with robust locator design and tolerance chain simulations, employing 3D analysis models and predefined tolerance limits to predict variations in critical product areas.

1.2 Purpose & Aim

This thesis topic will be a part of an advanced engineering project within the department of painted body, to make the simulation models more accurate. To build a simulation model of a body structure made of mixed materials, where some components are stiff structural elements, and others are thin, flexible sheet metal parts, introduces complexity to the simulations. This is hard to capture in a strict rigid body calculation. The possibilities are then to go over into a compliant calculation using FEM meshes, material models, and joining/contact modeling.

The primary aim of the thesis is to determine a way to optimize geometrical tolerance chain calculations, considering the correlation study conducted between real-world production data and different simulation methods. The study will mainly evaluate various simulation methodologies to enhance model accuracy and predictive capability. It will be conducted on a BIW upper body model from a Volvo Cars variant platform, selected for its complex mix of materials and critical joining structures. Results from both rigid body and compliant tolerance simulation models will be analyzed and compared to further optimize the geometrical tolerance chain calculations of the BIW parts. Based on the findings, the final objective is to present the comparison results between the various simulation models and real-world measurement outcomes, explaining the differences in terms of correlation accuracy, and to develop a fishbone diagram to identify the key contributors to the observed geometrical variations.

1.3 Research Questions

Based on the project's scope and aim mentioned earlier, the following research questions were formulated with the goal of answering them through the thesis's outcome.

- **RQ1:** How do different modelling strategies affect accuracy and model complexity for sheet metal assemblies?
- **RQ2:** What factors contribute to variations in sheet metal assemblies, and how can they be effectively modeled in simulation methods?

1.4 Limitations

The correlation study will primarily be based on real-world production data from the manufacturing plant in Charleston, USA. A major limitation of this approach is a potential restriction on data completeness, accuracy, and the ability to capture a detailed overview of part and process level variations. Additionally, since the data collection period is limited to approximately one year from the start of the running production. This narrows the scope of comparison and may exclude the variation trends that develop over a longer timeframe.

Another important limitation is the focus solely on the Upper Body BIW Assembly, as this is the only area for which the compliant model is developed within the project scope. Also, this compliant analysis can pose challenges, indicating a possible limitation in the required expertise. However, a Volvo employee specialized in this field has been involved to support and enhance the model development. Finally, the other limitation is the time constraint, which is about 20 weeks, limiting the depth of investigation into certain topics.

1.5 Summer Work Continuation

This thesis study builds upon the work conducted during the summer, where the initial phase involved a comparison using the entire BIW assembly that is *Upper Body, Front Structure & Rear Floor*. This analysis provided the insights for the comparison and served as a baseline for the thesis, which is now specifically focused on the Upper body assembly. So, the study aims to delve deeper into the geometrical variations and correlation studies within the upper body.

1.6 Body in White Assembly

BIW is a vehicle's foundational structure, assembling welded sheet metal components that form the entire internal structure before painting. The BIW Assembly image is shown in Fig. 1.2. This plays a crucial role in defining the overall geometry, stiffness, and aesthetic quality of the vehicle. Due to increasing demands for safety and sustainability, modern BIWs involve a complex mix of materials and are assembled using advanced joining techniques [6]. The geometrical variations within the assembly play a major role in managing geometrical deviations. As even minor dimensional variations can impact the overall assembly fit and function, the BIW has become a primary focus in GA efforts.



Figure 1.2: BIW Assembly of Volvo Cars XC90 [9]

1.7 Computer Aided Tolerancing

CAT refers to Computer-Aided Tolerancing, which uses digital tools and different simulation techniques to define, evaluate, and optimize the tolerances and assembly behaviour within the virtual environment. The tools like RD&T, VSA, CETOL, and 3DCS facilitate early detection of variation risks and allow for data-driven decisions regarding reference system strategy, joining sequences, and tolerance allocations [2]. By integrating CAT into the workflow, companies can reduce physical prototyping, shorten development times, and improve the robustness and manufacturability of their products [10].

For this thesis, the CAT tool RD&T has been used to compare and evaluate the performance of rigid body and compliant simulation models applied to a BIW upper body structure. Through this analysis, the goal is to assess how different simulation method approaches affect the accuracy of variation predictions and support improved geometry assurance in product development.

1.8 Geometrical Variations

The increasing accuracy in manufacturing technologies has greatly improved dimensional accuracy, but geometrical deviations remain an unavoidable aspect of the production process [11]. These variations stem from the deviations in the position and orientation of parts, even when produced under perfect conditions. It can come from

many different process-related factors and tends to show up at each stage of the product realization process. Moreover, these deviations do not just impact the product functionality but also the perceived quality of products [12]. For example, warping, welding distortions, and process adjustments may lead to these variations and will not be accounted for in the simulation models. In this thesis, these geometrical variations will be found by comparing the real-world production data with the simulation models and reasoning out the causes and contributors for these variations, especially within the Upper Body BIW Assembly.

2

Theory

The following chapter presents the literature review findings and explains the thesis's key concepts of geometry assurance and tolerance analysis.

2.1 Geometry Assurance

As discussed before in Chapter 1, Geometry assurance is an important process for companies producing physical products, particularly during the development phase [2]. This process consists of three important phases: concept, verification or pre-production, and production, which follows an iterative approach. The effective geometry assurance process helps minimize costs and avoid potential adjustments by ensuring a robust design through implementing an effective locating scheme. A locating scheme defines how parts are positioned and constrained during manufacturing and inspection, using a set of fixed reference points called locators. These locators ensure the repeatability of alignment and positioning of components, directly impacting the consistency and quality of the final product. Additionally, reuse of the locators from the previous assembly steps, instead of introducing new ones, is recommended to avoid new sources of variations [2]. In the concept phase, the main focus will be on achieving robust design and optimizing the locating scheme, which are critical in reducing geometrical variations between the simulation results and measurement data.

2.1.1 Robust Design

Robust design refers to the development of a product or process that is not affected by variations. This concept was originally introduced by Taguchi [2]. Robust design distinguishes influencing factors such as control factors, which are adjusted during the process, and noise factors that are difficult to control. The noise factors introduce variation, whereas the control factors are inputs to mitigate these variations. The robust design concept is illustrated using the P-Diagram in Fig. 2.1, which categorizes inputs into Signal factors (M), Noise factors (X), and Control factors (Z). These inputs collectively influence the response (Y) of the system, which defines the performance [13]. To achieve a robust design, optimization of the locating schemes concerning the part or assembly is required to minimize the variations. By systematically analyzing the influence of noise and control factors, the stability of a product's performance under real-world conditions could be enhanced. This makes robust design a fundamental principle in tolerance analysis and geometry assurance, especially in complex assemblies like BIW structures.

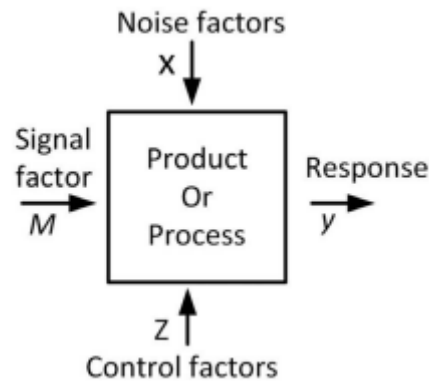


Figure 2.1: P-Diagram showing the factors [13]

2.1.2 Locating Schemes

Locating schemes are a crucial part of geometry assurance, and define how the part is positioned in space by fixture or other parts in an assembly. These points specify how these parts behave in a simulation analysis, and most importantly, to create a robust assembly. Variations will be introduced during assembly if they are not properly defined. They are used within different industries and classified as rigid and non-rigid locating schemes. A key principle in geometry assurance is often referred to as *“the main rule in geometry assurance”* is to use the same locating scheme consistently throughout part manufacturing, assembly, and inspection [2].

A rigid body locating scheme uses a 3-2-1 reference system, with six degrees of freedom. In this rigid body analysis, primary datums (A1, A2, A3) control three degrees of freedom, constraining the translation in the Z direction (TZ) and rotation around the X & Y direction (RX, RY). Secondary datums (B1, B2) control two degrees of freedom, constraining the translation in the X direction (TX) and rotation around the Z direction (RZ). Furthermore, the tertiary datum (C1) controls one degree of freedom, constraining the translation in the Y direction (TY). A non-rigid locating scheme introduces extra support and process points for defined over-constrained reference systems. This is especially done for the large automotive BIW parts like the Upper Body [2]. The Fig. 2.2 provides an overview of the rigid and non-rigid locating schemes.

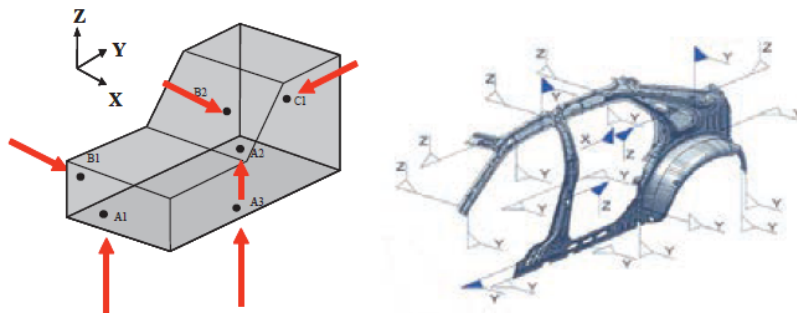


Figure 2.2: Rigid and non-rigid locating schemes [2]

2.2 Tolerance Management

Tolerances are implemented on engineering drawings to define the permissible variation in manufactured parts and to deliver final products that fulfill the functional and aesthetic requirements. Effective tolerance management is crucial, as tighter tolerances generally increase manufacturing complexity and costs. Therefore, balancing performance, cost, and quality is a key objective in the tolerance management process.

2.2.1 Tolerance Allocation

Tolerance allocation involves breaking down assembly-level requirements into individual components and key features of the part. It plays a crucial role in optimizing the balance between product quality, performance, and cost. Based on the final requirements, tolerances are systematically distributed across parts and features, which helps in identifying the key characteristics critical to function and manufacturability. Tolerances are often assigned based on functionality, drawing on engineering expertise, empirical data, and the chosen manufacturing process. The identification of a valid set of tolerances creating a balance between cost, desired part attribute, and quality is a challenging task. This allocation generally can follow either a top-down approach, where tolerances flow from the final product requirements to the part level, or a bottom-up approach, where generic tolerances are set based on experience and aggregated upward. In practice, these two strategies are often combined in an iterative process to ensure the overall dimensional robustness of the assembly [14].

2.2.2 Tolerance Analysis

Tolerance analysis, also known as variation analysis, is a critical step within the development phase of the product. This is widely used to ensure the functionality, manufacturability, and perceived quality of the product. There are several methods for calculating the sum of possible variations within an assembled component's stackup, based on the functional tolerance analysis or traditional fit-based analysis to derive optimal tolerance values. These stackup calculations will be the primary aspect to ensure that the parts or assemblies will reliably perform to customer specifications. These methods need to be analyzed further in multiple directions to decide which method to use for each direction, depending on factors like fit and performance of the product [15]. The three most common methods used for the tolerance analysis are: *Worst Case*, *Root Sum Squares (RSS)*, and *Monte Carlo (MC)* simulation methods.

The worst-case method calculates the maximum possible geometric deviation by summing up the variations of all connected components. This method helps to identify the potential failure condition within the assembly [15]. It relies on simple arithmetic operations to calculate optimized tolerances, and it is recommended for low production volumes. This method ensures 100% part assembly with zero rejection rate and also increases overall manufacturing and inspection costs as it requires tight component tolerances [16].

As a result of worst-case methods leading to excessively small and costly tolerancing, Statistical stack-up methods like the Root sum squares (RSS) and Monte Carlo (MC) methods were introduced in the early 1900s [15]. These methods further determine the probability of an assembly reaching a failure mode, such as being too loose or too tight concerning its required fit. The RSS method assumes that each component's geometric and dimensional variations follow a normal distribution, commonly represented by the classic bell curve called the Normal or Gaussian statistical distribution, characterized by a mean and standard deviation as shown in Fig. 2.3. This method estimates overall variation in a tolerance stack-up by summing the means and combining the standard deviations using the root sum square approach. RSS is widely recognized as a fast and efficient technique for analyzing combined tolerances, particularly in complex assemblies. Additionally, it supports design optimization and iteration by highlighting the sensitivity of individual GD&T parameters on the overall fit and functional performance of the assembly [15].

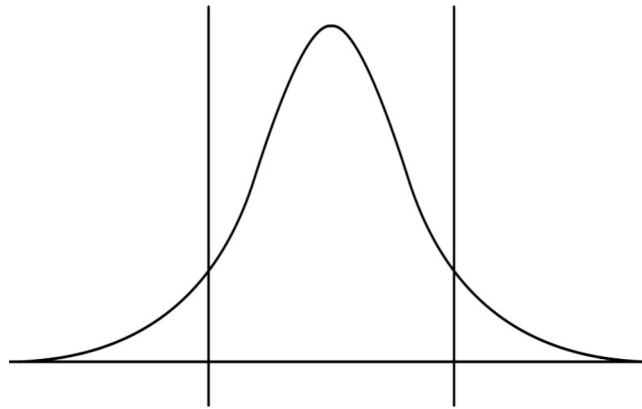


Figure 2.3: Normal or Gaussian statistical distribution curve [15]

The MC method is a computer-based analytical approach that uses statistical sampling techniques to approximate the probabilistic behavior of a model or assembly and the workflow is illustrated in the Fig 2.4. By generating sequences of random numbers as inputs, the MC method simulates how variations in component dimensions affect overall assembly performance. This method is well-suited for handling nonlinear models and complex assemblies. The primary objective of the MC approach is not only to improve product performance but also to reduce the cost through better-informed design decisions. The general procedure involves [17]:

- Randomly generating “ n ” sets of component-manufactured dimensions in an assembly based on specified statistical distributions.
- Get a sample of assembly functions employing the “ n ” sets of manufactured dimensions.
- Estimating key performance parameters such as the mean, standard deviation, sigma, and rejection rate.

Furthermore, the MC method is the basis for the majority of CAT software [17]. The automotive companies employ this method for the tolerance simulation analysis in BIW

Assemblies to determine the effective process without any errors, and this is the most commonly used method within the automotive industry simulation software.

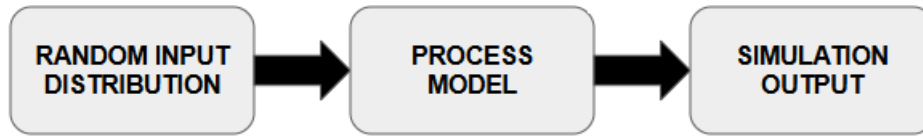


Figure 2.4: Monte Carlo simulation workflow

2.3 Tolerance Simulation Methods

The process of predicting the effects of different assembly characteristics, such as the variant assembly surroundings, the assembly sequence, assembly directions, assembly forces, gravitational forces, and assembly constraints [18]. Among the geometry assurance activities, virtual methods are increasingly important to ensure robust solutions as early as possible in the product realization process. Different simulation methods are discussed below in this section.

2.3.1 Rigid Simulation Model

This method performs tolerance analysis under the assumption of ideal rigid parts, ignoring any elastic or plastic deformation that might occur during manufacturing or assembly [19]. This model is suitable for assemblies with tight fits and rigid materials, and also comes with simplified analysis and reduced computational time and resources. Assembly deviations are also evaluated, accounting for variational features and constraints among the same parts. Variation modelling and analysis for multi-station assembly processes have been developed mainly for rigid parts.

The primary objective is to analyze how these geometric variations from the defined tolerances affect the final assembly, particularly in terms of fit, alignment, and functional performance. In practice, rigid body tolerance simulation begins with the import of 3D CAD models of individual BIW components, followed by defining the datums and specifying the tolerances for each assembly step continues for the whole body assembly. Statistical methods such as worst-case or Monte Carlo simulations are then applied to propagate the variation through the assembly model. These simulations evaluate outcomes of the statistical quality metrics (*C_p*, *C_{pk}*, *Range*, *Sigma*, and *Std*) across multiple build scenarios, providing insights into meeting the quality targets. Rigid body models are beneficial for analyzing large, stiff components, where deformation is minimal. They also support optimizing fixture designs and assembly sequences to minimize the impact of variation. However, since they do not account for the compliant behavior of thinner or more flexible parts, their accuracy is limited in assemblies where deformation plays a significant role. When combined with sensitivity analysis, these models offer valuable predictive capability to identify and prioritize critical tolerances

[20]. Ultimately, rigid body simulations provide a robust first step in a comprehensive tolerance analysis strategy, which may later incorporate non-rigid modeling for higher-fidelity validation.

2.3.2 Non-rigid Simulation Model

Rigid assemblies may be inadequate when parts exhibit high deformation. This particularly applies to some industries like automotive and aerospace, where sheet metal assemblies are commonly used. The high flexibility of such parts may cause wide shape variations during the assembly process, combined with tolerances on parts and fixtures. For non-rigid simulation, *FEA* (Finite element analysis) is included. This method allows over-constrained locating schemes that result in bending during assembly due to variation in parts and fixtures. This also captures the material properties, boundary forces, and external forces acting on the components. During a non-rigid simulation, deformation modes are computed under realistic constraints, allowing for a more accurate prediction of how part deviations and compliance collectively impact the final assembly outcome [21].

Joining sequence is crucial because variations in individual parts, fixtures, and welding equipment can affect the final assembly. The optimization is a non-linear problem and requires contact modelling [21]. The cycle time and position variation of the welding gun are simultaneously optimized. As vehicle designs evolve to incorporate lighter and more flexible materials, the role of non-rigid tolerance simulation continues to grow in importance for achieving dimensional robustness and manufacturability. The vast majority of the components that form the visible split lines on a vehicle are non-rigid sheet metal or plastic components [2]. The virtual assembly and scanned parts data play a major role in developing the non-rigid model in RD&T and in simulating the non-rigid behaviour of the intended process.

2.3.2.1 Virtual Assembly

A virtual fixture is a digital representation of a physical fixturing system used to simulate how non-rigid or compliant parts behave when they are positioned and constrained in an assembly environment. This concept is especially important for studying the deformation or variation of sheet metal parts, which can deform under gravity, residual stresses, or clamping forces. Unlike the rigid simulation method, this uses virtual methods to replace the physical verification in the fixture. This also includes the scanned part data to model how a part would behave when placed into the assembly setup. The scanned part, typically in its free form state, is virtually positioned following an over-constrained reference system with a defined set of support and process points to predict how the model would react under those constraints [22].

The modelling setup of virtual assembly has been presented in Fig. 2.5. This setup layout explains the process of developing the non-rigid model in a virtual assembly environment. The scanned parts data is collected in a free-form state to perform the assembly simulation in the RD&T Software. The process design/simulate stores information about the parts, sub-assemblies to be assembled, locating schemes, spot

weld points to be set, and their sequence. The MIC (Method of Influence Coefficients) accelerates calculations using efficient methods for contact modeling and weld sequence analysis [6]. The variation simulation is performed based on the Monte Carlo simulation [22]. It supports more accurate tolerance simulations by accounting for real-world compliance behavior, thereby improving the predictive accuracy of assembly outcomes in non-rigid simulations.

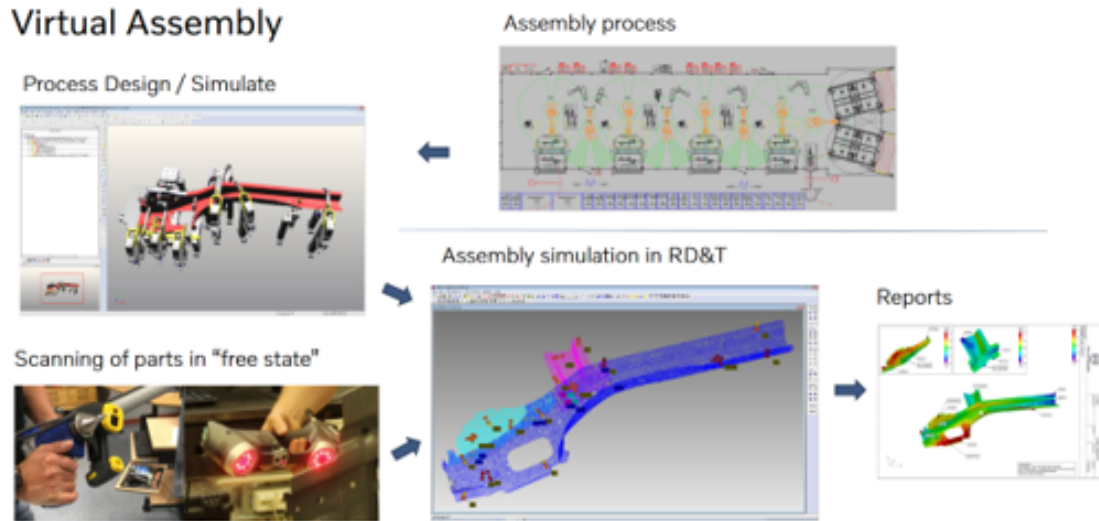


Figure 2.5: Virtual Assembly Modelling Setup [22]

2.3.2.2 Scanned part setup

In non-rigid simulation, scanned part data serves as a vital input to more accurately reflect real-world conditions. Unlike ideal CAD geometry, scanned parts capture the actual shape of components in their free form state, including effects from gravity, residual stresses, or manufacturing-induced deformation. These deviations are especially important in flexible sheet metal or plastic parts, where even minor inconsistencies can lead to significant variation once assembled. By using the scanned geometry as input, the simulation can represent how the part would behave when positioned into the assembly, providing a more physically accurate model. The setup of a part on the horizontal measurement base plate with three supporting spheres is shown in Fig. 2.6.

To capture the free-state shape of a part, a structured scanning procedure is used involving three height-adjustable supports with spherical tops. These supports are given to ensure the part rests on well-distributed, near-parallel surfaces, avoiding interference from sharp radii. Once the part is placed on the supports, it is scanned to record its shape in this resting condition. After removing the part, a second scan is performed to capture the positions of the three spheres and a section of the base plate, maintaining the same alignment. This process provides three essential point clouds: the shape of the part in its free-supported state, the exact locations of the three supports, and a reference plane aligned perpendicular to gravity. These datasets are crucial for

virtual fixturing and non-rigid simulation, enabling accurate development of the part's deformation under given constraints [22].



Figure 2.6: Scanned Part Setup [22]

2.4 RD&T

Volvo Cars uses the tool RD&T (*Robust Design & Tolerancing*) for geometry assurance activities, the software for dimensional control, tolerance analysis, and statistical simulation variation. This software enables the effect of manufacturing and assembly deviations to be simulated and visualized before any physical prototypes are made [23]. These capabilities are important in identifying the critical tolerances, tolerance chains and assess the robustness of a design early in the development phase. By integrating RD&T into the geometry assurance process, tolerances and assembly sequences can be optimized, as well as generate a fast and efficient inspection program, allowing individual adjustments in production [23].

RD&T allows for statistical analysis and simulation of variation to predict perceived quality. Another common type of analysis that is used is contribution analysis, which identifies the contribution of each tolerance factor that contributes to variation.

2.5 Perceived Quality

PQ (*Perceived Quality*) is defined as the customer's visual observation of the quality of the product, which for vehicles primarily relies on the relation between outer surfaces. Split line quality is an important aspect of the research area of perceived quality, which is also illustrated in the Fig. 2.7. Understanding this from the customer's point of view and its realization throughout the product development process is important to be able to balance requirements and allocate resources. When the components

are assembled into a product, the division between the components is defined as a split line. The final variations in these split lines are limited by so-called aesthetic geometrical requirements [24].

Visual quality is the most important aspect, with around 70% of the total importance, and it can be decomposed into several modalities. One such quality, called geometrical quality, is divided into four attributes that are gap, parallelism, flush, and reflection alignment. The visual quality impression will be lowered due to the wide gap and non-parallelism of the split line [25]. Gap refers to the distance between two adjacent components, while flush refers to the alignment of the two surfaces in depth or height. These are also called final quality demand, and if not met, can negatively impact the perceived quality of a car.



Figure 2.7: Images showing split lines of an Volvo EX30 Car

2.6 Process Statistical Parameters

In tolerance simulation and geometry assurance, process parameters play a key role in capturing how manufacturing variations occur. These statistical values describe how parts or subassemblies can deviate from their ideal dimensions, helping to understand and predict the range of variation across an assembly. Understanding these parameters is essential for accurately simulating variation, predicting assembly outcomes, and assessing the robustness of the final product.

2.6.1 Tolerance Range

The range refers to the difference between the maximum and minimum observed values in a dataset. In manufacturing and assembly, it indicates the spread of dimensional measurements across a batch of components. Although the range is easy to interpret and provides a quick understanding of extreme variation, it is highly sensitive to outliers and may not accurately represent typical process behavior. In simulation, the range is often used in early assessments, but is usually complemented with more robust parameters like sigma and C_p .

2.6.2 Sigma

Sigma (σ) is the standard deviation of a measurement dataset and is a fundamental measure of variability in statistical process control. It represents the average distance of the data points from the mean value and reflects the natural variation of a manufacturing process. In tolerance simulations, the use of 6σ or 8σ intervals is common to visualize the expected spread in assembly features. A lower sigma value indicates a more consistent and stable process, while a higher value implies greater uncertainty and variation.

2.6.3 Process Capability (Cp)

The Process Capability (Cp) defines how well a process can produce parts within the given tolerance limits [26]. It evaluates the potential of the process and is calculated as:

$$Cp = \frac{USL - LSL}{6\sigma}$$

Where USL and LSL are the upper and lower specification limits, respectively. A higher Cp value (typically 1.33) indicates a greater degree of capability and suggests that the process can reliably produce parts within the tolerance range. This method of Cp assumes the process data follows a normal distribution, and if the distribution is skewed, it cannot reflect the true capability of the process. Cp is particularly useful in tolerance allocation, as it helps prioritize which features or parts need tighter control to meet functional and quality requirements. In simulations, assigning accurate Cp values improves prediction accuracy and aligns the simulation model more closely with real production performance.

2.7 Measurement data

During the building of physical test series and prototypes, inspection is an important activity to understand as much as possible about the product and the processes. When full production starts, the main goal of inspection shifts towards quality control and the detection of deviations and variation. An efficient inspection process can lead to the faster detection of deviations, thereby avoiding costly adjustments and cancellations. The inspection of a part or assembly can be done by manual inspection, by inline inspection, by the use of checking fixtures, or by coordinate measurement machines (CMMs). Each method has its advantages and drawbacks when it comes to accessibility, precision, accuracy, and cost.

In automotive manufacturing, the measurement process of BIW assemblies is classified into inline and offline methods, each used for very critical roles in quality assurance. Inline measurement incorporates measurement systems directly into the assembly line to check the real-time monitoring of component quality. These systems are usually equipped with laser scanners and laser radar (LADAR), which perform non-contact,

high-speed data acquisition. Zeiss cell system utilizes optical 3D sensors to perform comprehensive inspections of BIW structures with high precision [27]. Offline measurement usually involves transferring BIW assemblies to the metrology labs equipped with a Coordinate Measuring Machine (CMMs) or laser scanning systems. These setups offer higher measurement accuracy and are typically used for detailed inspections, validation of critical dimensions, and root cause analysis of defects. A study comparing inline and offline systems found that the inline methods offer speed and integration benefits, whereas offline systems provide superior accuracy, which makes them indispensable for comprehensive quality assessments [28].

3

Methods

This chapter presents the detailed workflow of the steps taken during the implementation of the proposed methodology and the methods utilized to present the data plots and graphs, with some detailed explanations. It also presents the literature study and describes the interview approach employed to gather insights, and provides an overview of the simulation and measurement data setup.

3.1 Methodology

The methodology of this thesis is based on the principles of *Design Research Methodology (DRM)*, which supports the study through iterative phases of understanding, analysis, and refinement [29]. This methodology is adapted for the thesis and structured into three progressive phases, each contributing to enhancing the accuracy of tolerance simulation models within the BIW assembly process. These include: *Qualitative Analysis Phase*, *Quantitative Comparison Phase*, and *Final Optimization Phase*.

The initial step of *DRM* is Research Clarification, which defines the research problem, objectives, and context. It involves understanding the key concepts and identifying the gaps in existing knowledge or methods through a literature study and preliminary review of the data. The second step is Descriptive Study 1, which describes the existing situation through understanding the empirical data collection. This also includes the data gathered from the expert interviews to understand the current state of the process.

The third step is Perspective Study, which enables to development based on the insights collected from the previous steps. This also includes the analysis of the data gathered from comparisons and interviews in order to optimize the final model. The final step is the Descriptive Study 2, which evaluates the optimized model and assesses the effectiveness and impact, leading to refined recommendations and validations of the research outcomes.

3.1.1 Qualitative Analysis

As a part of this phase, an in-depth literature review was conducted alongside a set of interviews with the geometry assurance experts and the production team from the Charleston plant. The main objective of this phase is to get a comprehensive understanding of the existing simulation workflow and the methodologies. Tolerance

simulation data and corresponding measurement data from the assembly process were compiled and organized to enable a comprehensive correlation study.

3.1.1.1 Literature study

The literature study was conducted to establish a strong theoretical foundation and understand the key topics related to this thesis. To ensure the best outcome, the papers were selected based on the project's aim and key objectives. The study primarily involved searching through online academic databases, including *Chalmers Biblioteket*, *ScienceDirect*, *ResearchGate*, *ASME*, and *Google Scholar*. Academic papers and literature were the primary sources from which the information was obtained. All sources were initially reviewed by reading their abstracts, and those that seemed relevant to the thesis were selected for detailed analysis. These selected sources were analyzed to gain a deeper understanding and support the validation of the study's findings. By using specific keywords, a wide range of sources and papers were found, and they are used for the sake of relevance and filtration. Such keywords are:

- Geometry Assurance
- Rigid and Non-rigid simulation
- Geometrical Variation
- BIW Assembly sequence
- Evaluation of geometric tolerances
- Simulation Optimization
- Process Parameters
- Inspection Planning
- Part Variations
- Locating Scheme

3.1.1.2 Initial Interviews

Three semi-structured interviews were conducted to gain a comprehensive understanding of the simulation methods -Rigid and Compliant analysis, and to develop a deeper insight into the assembly process workflow at the Charleston plant. These interviews were mainly focused on presenting the results from the summer work and gathering the initial feedback through open-ended discussions. They acted as a preparatory step to gain a general understanding of the existing simulation models and the BIW assembly process, while identifying key challenges and highlighting relevant areas for further investigation. Based on the insights from these interviews, a more detailed comparison study has been conducted using different tolerance simulation methods.

All interviews followed a semi-structured format, guided by a predefined set of questions focused on specific topics within geometry assurance, as outlined in the Appendix A.1. This approach provided a better balance between consistency across interviews and the flexibility to ask follow-up questions if more information is needed. Both on-site and online interviews were conducted depending on the participant's availability. All the responses were transcribed and stored for future reference and analysis.

3.1.1.3 Simulation Models Setup

This thesis focuses on the evaluation of two tolerance simulation models within the RD&T software - the Rigid simulation model and the Compliant (non-rigid) analysis model. The selected BIW assembly model for this analysis was the *Body Side Complete (BSC) Assembly*, which is a critical sub-assembly within the Upper body structure of the entire BIW Assembly. This particular assembly was chosen due to its significance in the overall geometry within the BIW assembly process. The Fig. 3.1 illustrates the BSC assembly model used in this study.

This BSC assembly has served as the primary reference for both simulation approaches, giving a consistent basis for the correlation study. Both the simulation models were thoroughly checked for any errors, inconsistencies, or setup issues that could affect the accuracy of the final results. Ensuring the accuracy of these models was an important step to be addressed before conducting a correlation study with the measurement data.

Rigid Simulation Model

As explained in the section 2.3, the *Rigid simulation model* assumes that all parts remain undeformed during the BIW assembly process, focusing on the geometrical variations caused by the part locating system and tolerance stack-ups. This model is developed in the RD&T Software up to the BSC assembly level. The model setup is based on the reference data from the PMI (Product manufacturing information) and internal Volvo documentation, ensuring that the model closely aligns with the real-world assembly constraints and locating schemes. However, the rigid model does not account for deformation, but it will have the advantage of faster computation times.

The key part of a rigid simulation model is the 3-2-1 positioning system, which constrains the part or sub-assembly within this model in a defined reference coordinate system. So, this model is inherently not able to capture the effects from additional clamps or locators that would be used in a real-world assembly process. These extra supports can contribute to the final variations in geometrical deviations, but this could not be captured in a strict 3-2-1 configuration. To address this issue, the model will often be developed using alternative assembly setups. This alternative assembly refers to a modified configuration within a rigid model to reflect the actual assembly practices. This method uses different locating or positioning strategies on a single part level or sub-assembly level, to make the model closer to reality. By incorporating alternative assembly setups within the rigid simulation model, it becomes a closer representation of the real-world process and will further improve the correlation and alignment with the measurement data.

Compliant (Non-rigid) Simulation Model

The *Compliant model* presents the flexibility and deformation of parts during assembly. Unlike the rigid model, this simulation considers the sheet metal parts scanned data, giving a more accurate prediction of geometrical deviations that arise due to deformations and material properties. The compliant model is developed within RD&T Software using scanned part data from the November 2022 TT Series. The TT series is an internal Volvo project development name assigned to specific phases. This

model simulates the influence of different forces, such as welding, clamping, and joining operations, providing a more realistic representation of how parts behave within the actual production. However, the model is complex to develop and computationally not feasible when compared to rigid simulation, but it provides valuable insights that are crucial for the assembly process.

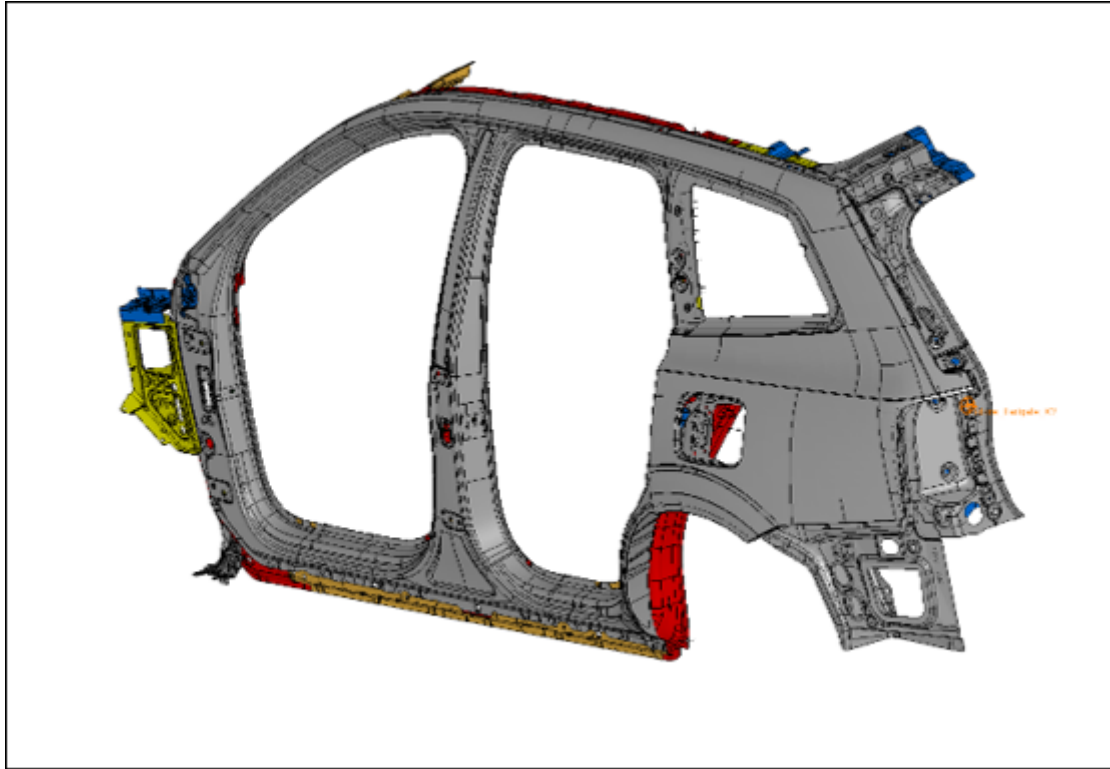


Figure 3.1: Body Side Complete Assembly

3.1.1.4 Body Side CPL Assembly

The BSC assembly consists of two key subassemblies: *Body Side Inner (BSI)* and *Body Side Outer (BSO)*. During the initial study, it was observed that BSO, due to its long and elongated geometry, is highly sensitive to variation and further risks the overall reliability of the final results. Therefore, all the BSO measurement points were excluded from the scope of this study to maintain the accuracy and consistency in the analysis. However, the other two parts, that is *PA Drain Channel* and *Uniside Ext*, were only considered due to their relevance and relatively stable behaviour.

The main focus of the study is on the BSI sub-assembly, which forms the central structure and plays a major role in the upper body and key factor in determining the dimensional accuracy. Pre-assemblies such as *PA T*, *PA Spider*, and *PA RR Qtr* within BSI have been included as they contribute significantly and have the critical measurement points. A total of 47 MPs within these pre-assemblies were considered for detailed comparison between simulation and production measurement data. This focused selection allowed for a more reliable and insightful assessment of geometrical variation within the BSC assembly process. The fig 3.2 illustrates all the PAs within

the BSC Assembly for a better understanding.

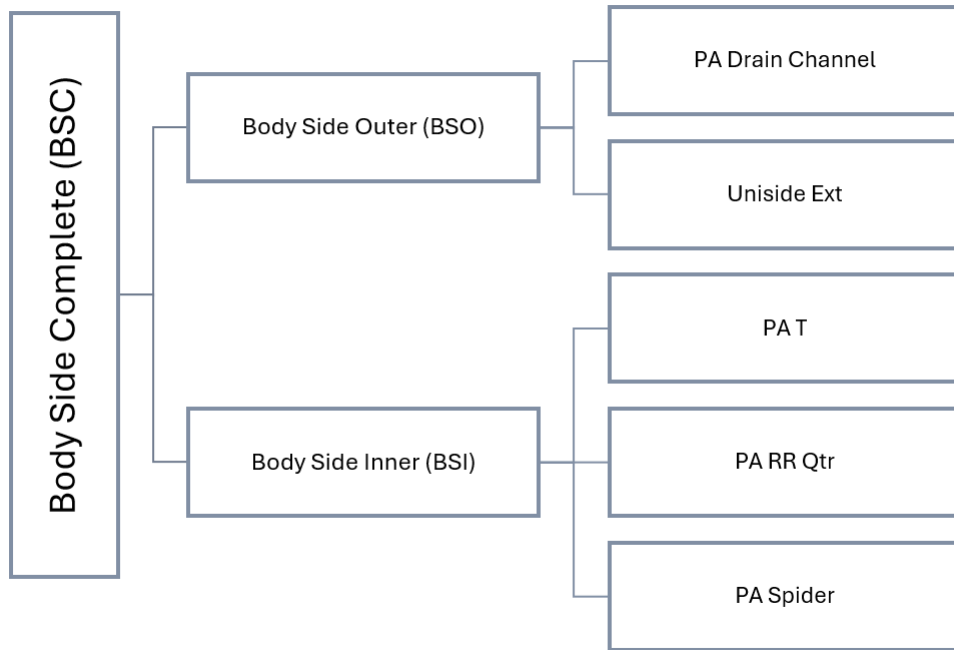


Figure 3.2: BSC Assembly Flowchart

3.1.1.5 Simulation & Measurement Data Setup

The correlation study in this thesis is mainly focused on comparing two datasets - simulation data generated from RD&T software and measurement data extracted from CM4D software. The simulation data were collected from both rigid and compliant simulation models, each offering different types of output depending on their respective configurations. Rigid model provides a set of process parameters, including statistical values such as *range*, *6 sigma*, and *8 sigma* used to compare the variation within the measurement data from the BIW assembly process. The compliant model is developed using single-part scanned data as explained before in the section 3.1.1.3, and limited to its output to *mean shift values*. Since the compliant model is built using data from a single scanned part, it does not represent part-to-part variation, and therefore cannot produce statistical variation results like those generated within rigid simulation.

Measurement data used for this study were collected from the CM4D software, covering the period from *June 2024 - February 2025*. This particular dataset represents running production data from the BSC assembly line, capturing real-world variations within the assembly process. The timeframe is recommended by the production team from the Charleston plant as the assembly process became more stable and robust during this period. Using the stabilized measurement data ensures that the correlation study will be more accurate and minimize the variations or outliers.

To ensure a consistent basis for the comparison, MPs (measurement points) defined at the BSC assembly level were used as a reference to update both simulation and

measurement datasets. The same MPs were used to extract and update the data from each source, enabling a comparison between the two datasets. These datasets were then compiled and organized using an Excel sheet for the correlation study.

3.1.2 Quantitative Comparison

In this phase, after the data collection, a structured comparison is done to evaluate the accuracy of the datasets. Simulation data is compared against measurement data by organizing the datasets while visualizing variation patterns and key factors. A correlation study is performed to determine the alignment between the simulation data and measurement data, offering insights into the reliability of the simulation models. To understand the discrepancies between the datasets, in-depth interviews were conducted to determine the root cause analysis. Finally, a fishbone diagram is shown to summarize the key factors or contributors to the geometrical variations within the BSC assembly.

3.1.2.1 Dataset Preparation

The simulation and measurement data were compiled in an Excel sheet, which was chosen mainly to handle these large datasets and the compatibility with other analysis tools such as MATLAB and Power BI. In the Excel sheet, all the MPs data is updated according to their respective PAs (pre-assemblies). Additional attributes, such as locating hole, coordinates, and the reference point side, are mentioned to support a more detailed comparison. Custom formulas were implemented to calculate the comparison of tolerances and sigma values across both simulation data and real-world measurement data. Compiling the measurement dataset was a significant task, involving around 8,500 samples. It was carried out properly to ensure accuracy and prevent any data misplacement.

During the initial review of the measurement data obtained from CM4D Software, many outliers were detected. These outliers are abrupt jumps in the measurement data that did not align with the normal production trends. As shown in Fig. 3.3, these anomalies are due to temporary process disturbances or specific assembly issues usually described as the noise factors. To maintain accuracy and further not jeopardize the final results, these outliers are excluded from the dataset. The verified data were then recompiled into an Excel sheet and used as the baseline for further statistical comparison and correlation studies.

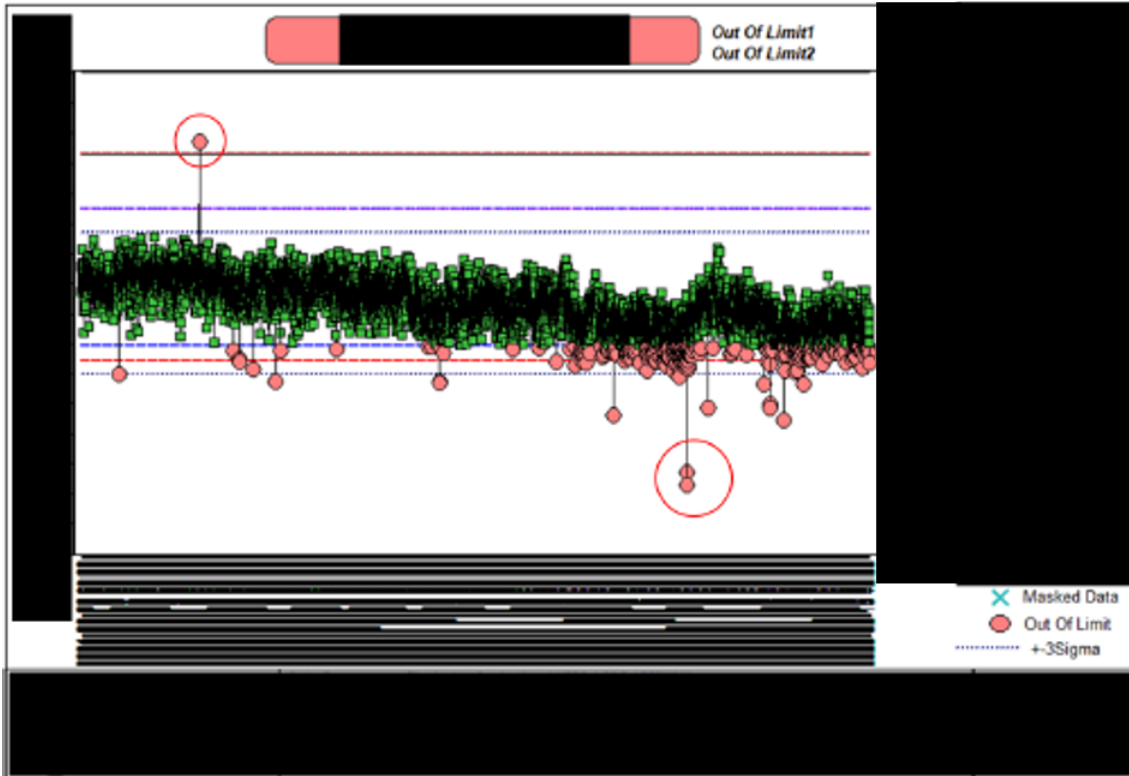


Figure 3.3: Measurement point data in CM4D highlighting outliers. Confidential information covered.

3.1.2.2 Dataset Visualization

To better understand the relationship between the simulation and measurement data, *Power BI & MATLAB* tools were used to visualize the results. Scatter plots were created to directly compare the simulation values (8σ) and real-world measurement values (6σ), making it easy to analyze the patterns and correlations. Interval plots were created mainly to project the mean shift of the measurement points to compare them within the tolerance range band from running production. To maintain confidentiality and comply with Volvo's internal data protection, the plot numerical values were not shown. This approach ensured that no sensitive data was disclosed while still preserving the variation patterns necessary for analysis. These visualizations not only made the study easier but also supported clearer discussions within the team to find the variations between the datasets.

3.1.2.3 Correlation Study

The simulation and measurement data were compiled and visualized using the Power BI and MATLAB software for the correlation study. This study in this thesis aims to evaluate how accurately the simulation models represent the real-world production data. The key part of the analysis within the plots is based on comparing the 8σ values from the simulation with the 6σ values from the measurement data. This approach was chosen because simulation models, especially rigid ones, do not capture the real-world process effects. So, to maintain this extra margin and by comparing

8σ with 6σ , the results can be better aligned and account for the variations that are not fully captured in the simulation environment. Measurement points serve as the reference to compare these two datasets.

This study further involves the analysis of statistical parameters such as range and sigma values for individual MPs within each pre-assembly. By assessing these values, the correlation study helps to evaluate how each pre-assembly responds to variation and whether the simulation models effectively capture the real-world process effects. This quantitative assessment forms the basis for determining the accuracy of the models. The outcomes of this analysis help in identifying key discrepancies and variation trends, which guide the optimization phase further.

3.1.2.4 In-depth Interviews

Following the initial interviews conducted with geometry assurance and production experts, in-depth interviews were conducted with the same participants to delve deeper into the insights gathered from the preliminary comparison and results. These interviews were mainly focused on presenting the early findings from the rigid and compliant models in comparison with measurement data. The main purpose is to validate observations, identify root causes, and gain expert input on potential factors for variation.

Similar to the previous interviews, the in-depth interviews were individually tailored to each participant's area of expertise and structured using a combination of semi-structured and unstructured formats. The semi-structured part is followed by an interview guide with a predefined set of questions, while the unstructured part is primarily for gathering descriptive opinions and facilitating open-ended discussions. This format was flexible and encouraged the participants to elaborate on the complex issues, without disrupting the flow of their insights [30]. These discussions also helped determine the RCA (Root Cause Analysis) to identify key factors, such as process adjustments and data inconsistencies.

3.1.3 Final Optimization

The final phase of the methodology focuses on the optimization of the rigid simulation model, using insights from the correlation study and interviews. This phase mainly aims to improve the predictive accuracy of the rigid simulation model by refining key statistical parameters and addressing variations identified while comparing with measurement data. This optimized model then serves as a foundation for developing recommendations and best practices for future BIW platforms within geometry assurance.

3.1.3.1 Root Cause Analysis

Root Cause Analysis is a structured method used to identify underlying causes of issues that stem from individual process deviations or system-level inefficiencies. In the context of BIW production, RCA is applied to assess the assembly process,

which may involve both serial and parallel subassembly structures, depending on the product's complexity. For example, in a serial assembly, components are assembled in a defined sequence to build up subassemblies progressively. A virtual tool like RD&T is utilized to conduct the RCA, revealing both the variations and deviations. Furthermore, the model in the tool can be updated with the inspection data from the final product, enabling an analysis of the assembly and its locators to identify the root cause of identified issues [2].

Before working on the optimization within the rigid simulation model, it was essential to gather and understand the findings from the Root Cause Analysis. These insights were derived from the correlation study and the interviews conducted with the geometry assurance and manufacturing experts. Through this process, several issues were identified, such as process adjustments, an improper locating system, and a lack of consideration of certain process constraints within the rigid model. This analysis laid a solid foundation for guiding the optimization efforts and ensuring that the model is closer to reality.

3.1.3.2 Final Optimized Model

As the root causes are clearly defined, the next step involves optimizing the rigid simulation model within the RD&T software. Since this model assumes no deformation in parts, the focus was placed on optimizing inputs that heavily influence geometric outcomes, such as locating schemes, tolerance stack-ups, and reference point definitions. These changes were made iteratively based on the judgment gathered from interviews and the deviation patterns observed during the correlation study. The goal here is to make the simulation model capable of capturing the actual assembly behavior, but not just to reduce the gap between simulation and measurement data. This step will be very crucial to ensure that the simulation will become a more reliable tool for early-phase decision-making in BIW geometry assurance.

The optimization of the compliant simulation model was not done as part of this study due to several limitations. This particular model, while capable of capturing part deformation and actual assembly behavior, is significantly more complex to develop and requires advanced domain expertise that was beyond the current scope. As a result, the study prioritized optimizing the rigid model, where data and expertise were available, while the comparison methods and results of the compliant model were reserved for future work.

3.1.3.3 Simulation Guidelines

Simulation guidelines are a specific set of recommendations provided based on the study of BSC assembly. As the optimized simulation model has shown some improved alignment with real-world data, the final step in this phase was to document and formalize the updated simulation practices. A revised set of simulation guidelines was created specifically for the BSC assembly, incorporating all the learnings and developments from the optimization process. These guidelines will be included with recommendations stating which simulation method is reliable in capturing the particular PA,

selecting reference points, applying tolerances, and interpreting outputs within RD&T. The intent is to provide detailed reference data for geometry assurance engineers to support consistent and accurate model creation for future platforms. By aligning these practices with actual production conditions, the guidelines will further help to close the gap between digital simulations and physical outcomes.

4

Results

This chapter presents the detailed analysis of rigid and compliant simulation results and also explains the root cause analysis of each PA causing variations within the BSC Assembly. Finally, the fishbone diagram and an optimized rigid simulation model, along with the guidelines, have been presented.

4.1 Initial Interviews

The interviewed engineers are part of the *R&D - Geometry Assurance* team and *Charleston Manufacturing* team within Volvo Cars. All these engineers are involved in the geometry assurance process to a great extent and have worked on the BSC assembly of the specific variant that has been considered for this thesis study. These engineers were recommended by the supervisor himself. The engineers who took part in the interviews were the following, and their work area is also mentioned:

- GA Engineer (**GE1**): *Compliant Analysis Expert*; Painted Body Commodity - Hang on parts
- GA Engineer (**GE2**): *Upper Body Expert*; Painted Body Commodity - Upper Body
- Manufacturing Engineer (**ME**): *Upper Body Manufacturing*; Painted Body Industrialization

These interviews primarily focus on presenting the comparison results obtained during the summer job, which lasted approximately one hour each. After the initial presentation of the comparison study with the old measurement data, a detailed discussion about the major deviations within the assembly process and the rigid and compliant simulation models workflow was discussed. *GE1* explained in detail about compliant analysis and how to interpret the compliant simulation results within the RD&T Software. The explanation also covered the steps involved in developing a compliant model and the time frame required for its implementation. *GE2* emphasized the importance of the Upper body assembly, highlighting the critical role in the BIW assembly process. Key aspects and major contributors were also described within this BSC assembly process. *ME* offered a clear overview of the BSC assembly process, identifying the key contributors for the geometrical variations within the different sub-assemblies.

4.2 Rigid simulation Model

This section outlines the step-by-step improvements made to the rigid simulation model in RD&T Software, focusing on enhancing its predictive accuracy and correlation with the measurement data. The work began by analyzing the initial simulation setup and comparison results from the earlier summer job, which showed several variations between the two datasets. Using these findings as a preliminary baseline, a series of improvements has been made to the rigid simulation model, which is briefly explained in the sections below. At each stage, a comparison is made between the simulation and measurement data to evaluate progress and verify correlation accuracy.

The initial comparison between the rigid simulation data and measurement data was presented in Fig. 4.1. At this stage, no improvements were made to the simulation model, and the measurement data used for comparison were collected from May 2024 to June 2024 as part of the summer job. This comparison serves as a baseline to understand the initial correlation accuracy and average difference between the two datasets. It provides a reference to demonstrate how both the correlation and average difference were improved in the later phases of the study following model optimization.

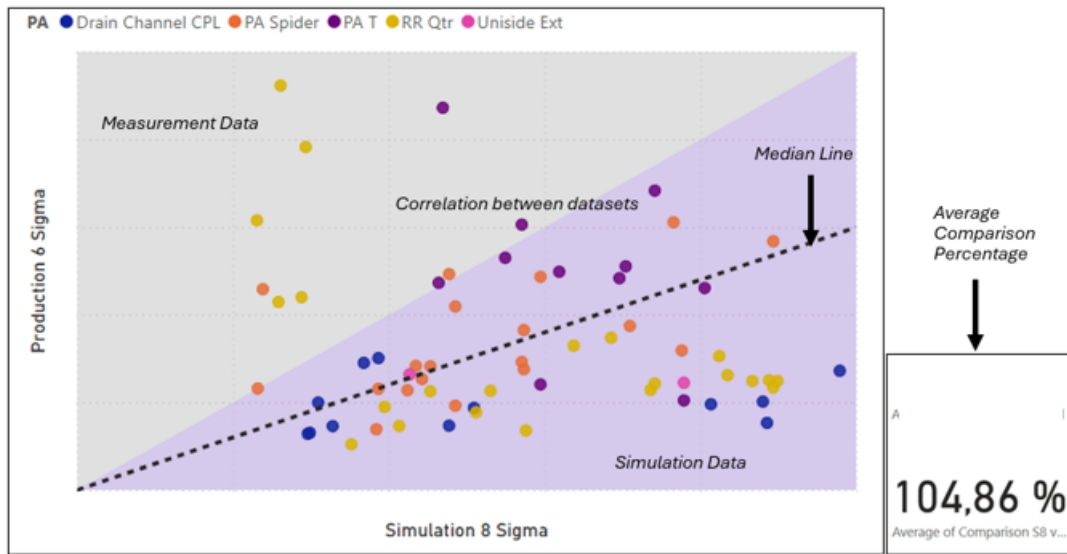


Figure 4.1: Scatter plot comparison between rigid simulation data and measurement data (old)

As previously mentioned, this interactive plot was created using Power BI, with a detailed description provided in the Appendix A.2. This particular plot helped verify all the slicers and made it easier to understand the variations by allowing individual inspection of each MP. As shown in Fig. 4.1, the plot displays simulation data on the X axis and measurement data on the Y axis, effectively illustrating the correlation accuracy between the two datasets under the given attributes. A median line is included to show the relative magnitude of the values. In this case, the line is shifting towards the simulation axis, suggesting that simulation values are higher than measurement values. Additionally, an average comparison percentage has been done

to show the percentage difference between the simulation and measurement data.

From this initial comparison, it is evident that simulation data is significantly larger than the real-world measurement data. This difference is primarily due to the limitations of measurement data, which include a smaller sample size and inconsistencies within the process from earlier data collection. Additionally, the rigid simulation model did not undergo any improvements or optimization, which limited the ability to capture the process variations observed in real-world measurement data. It is also important to note that this model is developed during the earliest stages of the design phase of this particular variant. So, this baseline comparison highlighted the need for refinement to align the simulation model closer to reality.

4.2.1 Improvement 1 - Review Tolerances & Cp Values

The first step to improve the rigid simulation model involves a proper review and verification of the *tolerance ranges* and *Cp values (Process Capability)* used throughout the assembly structure. During the initial assessment, it became evident that some tolerance ranges and Cp values in the simulation model did not fully align with the latest product manufacturing data (PMI), which further impacts the accuracy of the simulation results.

To correct this, the model was systematically cross-checked against the official PMI documentation, along with the Cp value checklist provided by the Geometry Assurance team. The Cp value checklist was developed using several years of manufacturing data and is structured to reflect process stability based on single part characteristics such as material and function. The PMI data served as the primary reference for defining nominal dimensions and tolerance limits, ensuring that each feature and measurement point in the model reflected actual design intent. Similarly, the Cp values are critical for understanding the expected process stability and were verified and updated, if any incorrect input was found. The measurement data used for this updated comparison were collected over a longer period, from June 2024 to February 2025, as detailed in the section 3.1.1.5. Compared to the initial two-month dataset, the new measurement data was more robust, featuring a larger sample size and reflecting a more stabilized assembly process. This resulted in better range variations and improved 6σ values.

This improvement not only helped correct several inconsistencies but also laid a strong foundation for all subsequent improvements. Ensuring that the basic input parameters were accurate and consistent with document standards reduced variation in the simulation output and improved the overall model's reliability. Moreover, this step reinforced the importance of maintaining traceability between design documentation and digital simulations, which is an essential practice for geometry assurance work. Collectively, these refinements significantly enhanced the correlation between simulation and measurement data, bringing the simulation model much closer to real-world process variations. To ease the process and work with the rigid simulation model, both improvements 1 & 2 were updated simultaneously. Once these updates are made, the simulation model is compared against measurement data, and the comparison plot is

shown in Fig. 4.2.

4.2.2 Improvement 2 - Duplicated Tolerances

During the review of the rigid simulation model, one key issue identified was the presence of *duplicated tolerances* within certain sub-assemblies. These duplicated tolerances are typically the process tolerances assigned repeatedly across multiple build steps, even though the same positioning and locating system was used within different sub-assembly steps. This meant that the same source of variation was being calculated more than once in the simulation chain, eventually inflating the predicted deviations across the BSC assembly. This issue is very critical in tolerance simulations, as the addition of these tolerances is a core factor in determining overall variation. When the same tolerance is applied multiple times, the rigid simulation model assumes additional variation that doesn't exist in reality, leading to inflated variation results of the final assembly. Such discrepancies not only reduce the accuracy of the model but also mislead further analysis by highlighting variation trends that are not present in the physical assembly process.

A detailed inspection of the simulation model was conducted, focusing on the tolerance inputs associated with each assembly step. The build sequence and positioning systems were carefully reviewed to identify where these duplicated tolerances are applied. These entries were then removed to ensure that each source of variation was accounted for only once in the simulation. After cleaning up these duplicated tolerances, a notable improvement in the correlation with real-world measurement data was observed. This adjustment brought the model's predictions closer to reality, reducing inflated variation patterns and reinforcing the model's reliability as shown in the Fig 4.2. This step was essential in refining the simulation chain calculation and building a more accurate representation of the BIW assembly process.

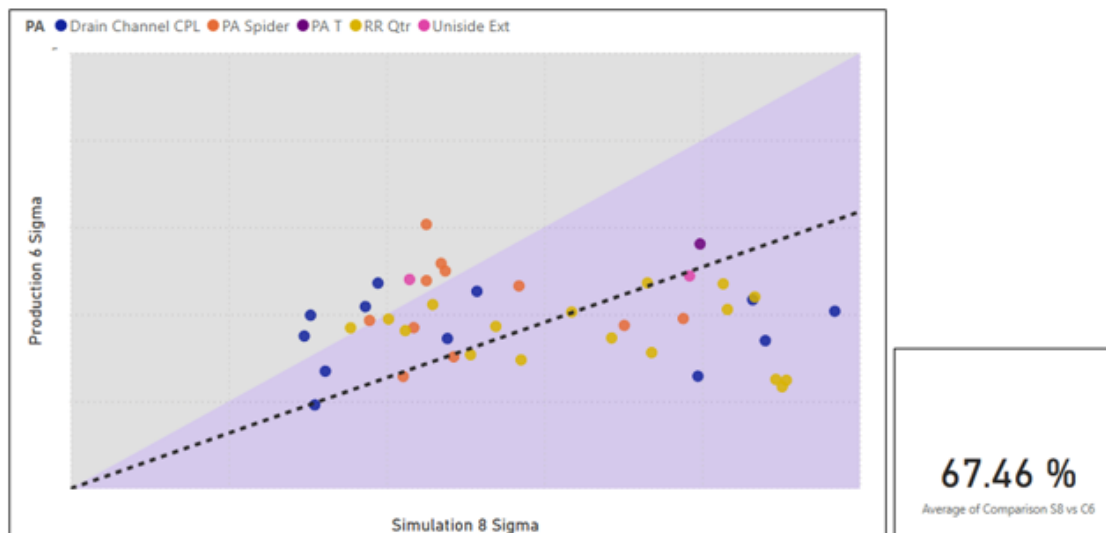


Figure 4.2: Scatter plot Comparison after tolerance & Cp value review and removing duplicated tolerances

4.2.3 Improvement 3 - Update Alternative Assembly

During the refinement of the rigid simulation model, it was identified that certain components within the BSC assembly, specifically the *Drain Channel* and the *D-Pillar*, were built using alternative assemblies. This means that these parts were positioned differently at the single-part level using alternative assemblies compared to the initial simulation setup. The alternative assemblies are usually created using different locating schemes, which are done to replicate the real-world positioning system. This discrepancy had a significant impact on the simulation accuracy. Since the MPs defined at the BSC assembly level were not aligned with the original configuration, the simulation did not correctly represent the assembly conditions for these parts. As a result, the deviation patterns generated in the model did not reflect the actual behavior observed in the production data.

To correct this, all MPs associated with the Drain Channel and D-Pillar were reviewed and updated with the alternative assembly defined on the single part level to match the locating conditions. This update has ensured that the simulation model was consistent with the actual positioning and build sequence used within the assembly process. By aligning the MPs with the alternative assemblies, the correlation between the simulation and measurement data has been significantly improved for these particular parts. This update played an important role in reducing the gap between the simulation and real-world outcomes. It highlighted the importance of accurately modeling assembly variations at the sub-assembly level, especially when alternative assemblies are used. As shown in the Fig 4.3, the scatter plot comparison after doing this improvement showed a significant improvement of 14%.

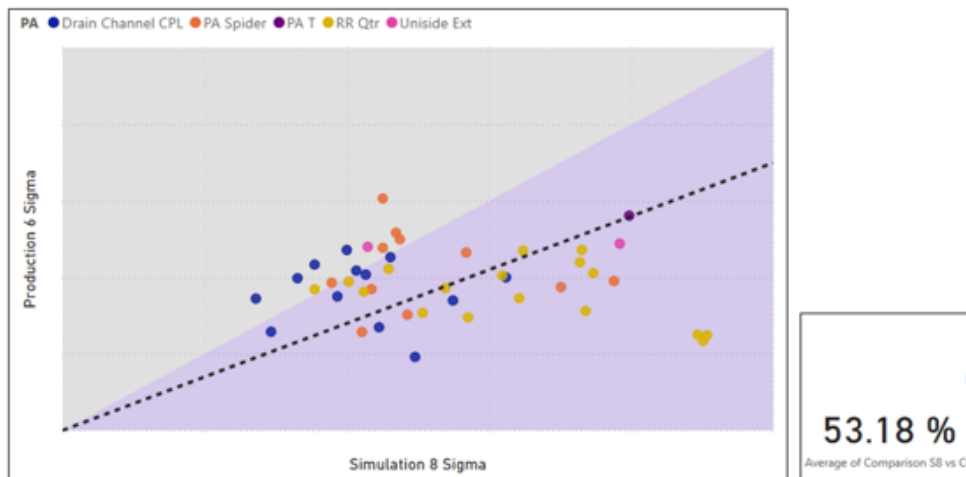


Figure 4.3: Scatter plot after updating the alternative assembly

4.2.4 Improvement 4 - Part Tolerance Cp Values

As the final step in refining the rigid simulation model, the focus was directed toward updating the part tolerances using real-world *process capability* (C_p) values collected from actual supplier production data. The objective of this phase was to evaluate how accurately the simulation model could reflect real assembly conditions when updated

with single-part level Cp inputs. To carry out this improvement, the process began by collecting Cp values directly from the CM4D software, using measurement data sourced from the running production. Specifically, the Cp Value Checklist, commonly shared across three variant platforms, is used as the foundational reference for updating Cp value input in the simulation model. This checklist provides a structured and consistent way to interpret and apply Cp values across different part levels.

Each part typically includes three primary feature types used for quality control and dimensional verification: *surface*, *edge*, and *hole* features. To ensure comprehensive data, five measurement samples from each feature type were carefully selected, which were spread across the part geometry. This approach helped capture localized variations while still maintaining statistical balance across features. Once the relevant points were selected, the Cp values from CM4D were compiled into an Excel sheet. For each feature type—surface, edge, and hole, an average Cp value was calculated to represent the overall capability of that feature on the part. These averaged values were then assigned to the respective components within the RD&T rigid simulation model. This ensured that the simulation tolerances were not just design estimations, but instead updated with actual production performance data.

However, one of the challenges encountered during this process was the limited availability of stable production data, particularly because the variant that has been used for the thesis study only started its running production recently. As a result, measurement data for some single parts were not consistent, and with shorter duration, which made it difficult to draw reliable conclusions. To uphold the quality and accuracy of the dataset, only parts with at least six months of consistent running production data were considered for this improvement phase. This filtering criterion ensured that only stable Cp values collected from the running production were updated in the model. The parts that were updated with single part Cp value data within the rigid simulation model is shown in the Fig. 4.4.

4. Results

Cp Value parts in Simulation Model		
S.NO	Part Name	Data
1	A PILLAR INNER UPPER L/R	8 Months
2	B PILLAR INNER L/R	8 Months
3	D PILLAR INNER LOWER L/R	9 Months
4	D PILLAR INNER UPPER L/R	8 Months
5	DRAIN CHANNEL CENTER L/R	6 Months
6	DRAIN CHANNEL OUTER L/R	8 Months
7	EXTENSION A PILLAR INNER UPPER L/R	6 Months
8	EXTENSION SIDE OUTER FRONT L/R	7 Months
9	LAMP PANEL L/R	7 Months
10	PANEL QUARTER GLASS L/R	8 Months
11	UNISIDE EXTENSION L/R	7 Months

Figure 4.4: Single Part Cp Value with consistent data

By updating the single-part Cp values into the rigid simulation model, the correlation accuracy and average were improved. This step helped to get the simulation data closer to the measurement data, which further increased the accuracy between the two datasets and served as a foundation for optimization of the model. These step-by-step improvements led to a significant transformation of the simulation model, enhancing both data accuracy and reliability. The correlation accuracy between the simulation data and the measurement data has been improved by 56%. It reduced the initial gap from the 104% down to around 49%. A key observation is the strong correlation between the two datasets, clearly reflected in the scatter plot. The majority of MPs align closely with the 45-degree reference line as shown in the Fig 4.5. This alignment actually signifies that rigid simulation is effectively capturing the process variations, demonstrating high predictive capability and reinforcing the model's reliability for future analysis.

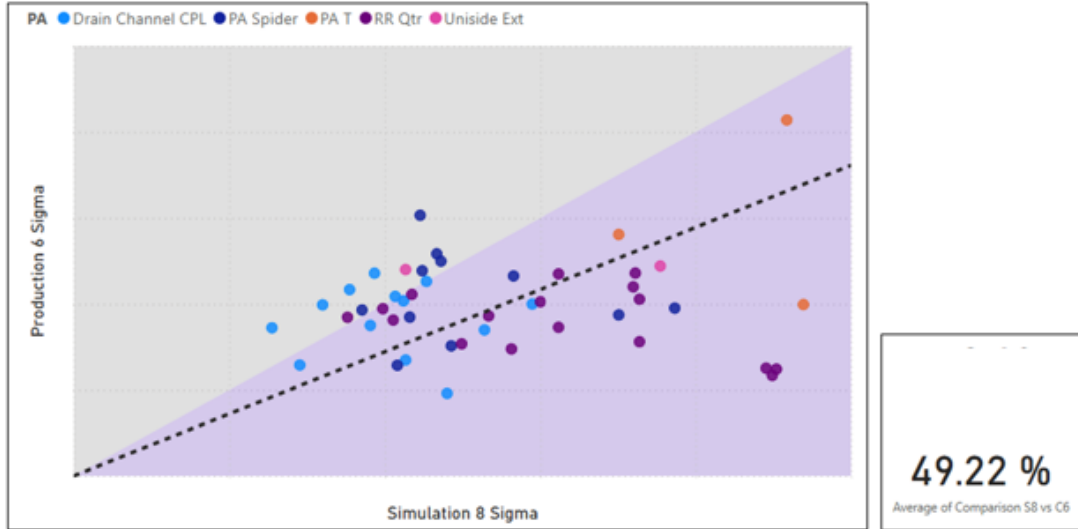


Figure 4.5: Scatter plot after Single part Cp Value update

4.3 Compliant Model results

As a part of this thesis, the Compliant Simulation Model was analyzed to gain a deeper understanding of how the measurement points are acting when compared with the real-world data within the BSC assembly. Unlike the rigid simulation model, which focuses mainly on geometric tolerance stack-ups and locating schemes, the compliant model simulates the physical behavior of parts, considering the material properties under real assembly forces such as welding, clamping, and joining. This approach provides a more realistic representation of the BIW assembly process. As discussed before, the compliant model used in this study was developed in RD&T software using single-part scanned data from the November 2022 TT Series. The objective was to accurately replicate the locating system setup used in the BSC measurement fixture, to evaluate the compliant analysis results at the BSC assembly level within RD&T Software. To achieve the alignment of the simulation setup with real production conditions, including factors like gravity direction, clamping strategies, and locator configurations similar to the real-world assembly process. The compliant model, being developed using a single scanned part dataset, does not capture the full range of variation. As a result, only mean shift values can be generated, while other statistical process parameters, such as sigma, range, or Cp cannot be extracted. Apart from this limitation, the analysis still offers valuable insights into how part deformation influences overall geometrical variation during assembly.

To assess the model's accuracy, the mean shift values from the compliant simulation model were compared against actual measurement data collected from CM4D. The analysis was carried out on the whole BSC assembly. For the comparison, measurement points were used as reference, and mean shift values were derived from the compliant analysis by going through each point individually. An interval plot is created to project these mean shifts and compare them with the measurement data mean shift. MATLAB is used to present the patterns of deviation and make comparisons more

intuitive.

Another challenge was the scope of the simulation itself, because only mean shift values were available, a full process-level statistical comparison, as done in the rigid simulation model, is not possible. This restricted the depth of the correlation analysis. Nonetheless, the comparison of mean shift data still provided valuable guidance in identifying potential gaps between compliant simulation and reality, and it helped reason out the performance of both simulation models within each individual PA.

4.3.1 Interval Plot with Multiple Mean Shift

So, to create this plot, all the simulation data from both rigid and compliant simulations, along with the measurement data, have been compiled into a single Excel sheet covering all relevant measurement points. This particular dataset has served as a comprehensive analysis and visualization of variation behaviour.

This interval plot was created to assess whether these MPs are consistent within the process variations. The primary aim is to evaluate multiple mean shifts, specifically those from the Compliant simulation model, Running production, and the TT Series, to understand how they align within the 6σ projection of the running production. Additionally, this also evaluates whether the 8σ spread from the rigid simulation model can effectively capture the 6σ variation observed in the running production. Here, the running production refers to the ongoing full-scale assembly process currently in place. The TT series represents the development phase of the particular variant conducted before the start of actual production. Since the compliant model was developed using the scanned part data from the TT series, the measurement data from this series is collected and compared with the Compliant simulation results.

All relevant data from both simulation models and measurement data were processed to create this particular plot in MATLAB as shown in the Fig. 4.6. A more detailed description of the plot is given in the Appendix A.3.

To briefly interpret this plot:

- The X-axis displays all the MPs, divided according to their respective pre-assemblies.
- The Y-axis represents the projection of multiple mean shifts, plotted against the simulation and measurement ranges.

This method offers a clear and structured comparison across datasets, enabling the identification of critical deviations and the reliability of simulation models.

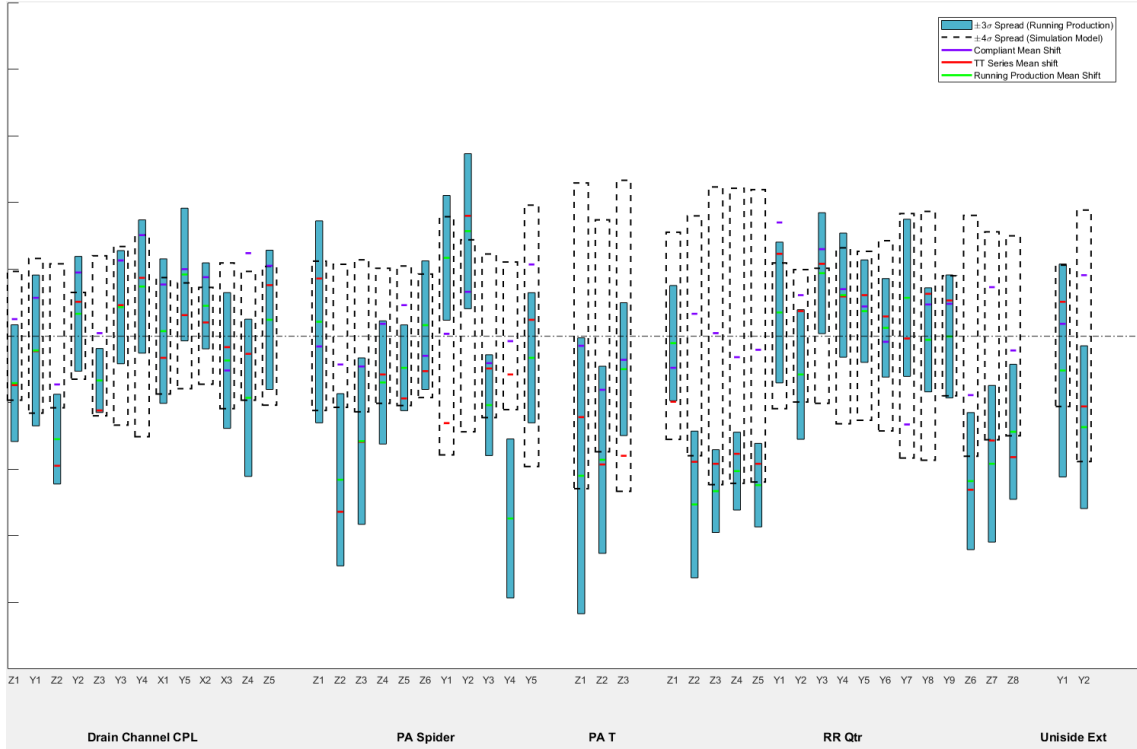


Figure 4.6: Interval Plot with multiple mean shift

In the interval plot, the blue bar represents the 6σ spread derived from running production data, capturing the range of variation during the assembly process. The dotted line represents the 8σ spread obtained from the rigid simulation model, serving as a reference to evaluate whether the rigid simulation is capturing the real-world process variation. Three horizontal lines are plotted to depict mean shift values from different sources as shown in the Fig. 4.7:

- Purple line indicates the Compliant model mean shift.
- Green line indicates the Running production mean shift.
- Red line indicates the TT Series mean shift.

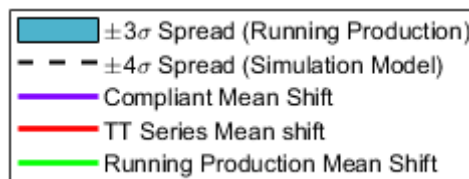


Figure 4.7: Legend of the Interval Plot

The following sections were explained briefly to give an understanding of these plots within different comparisons, highlighting how the compliant results reflect within different conditions and what insights were drawn from these analysis:

Compliant & TT Series Mean shift

The first comparison focuses on the Compliant model mean shift and the TT series mean shift as shown in the Fig. 4.8. As observed in the plot, the majority of measurement points closely align between the two datasets, indicating a strong consistency within the Compliant model analysis. This alignment validates the effectiveness of the model in capturing the part behavior based on the scanned data from the TT series. However, a few deviations are noted, particularly within the PA RR Qtr, PA Spider, and PA Drain Channel sections. These outliers are likely due to process adjustments or changes that occurred during production, which were not reflected in the scanned parts used to build the model. It is important to note that the Compliant model in this study was developed using a single scanned part, which inherently limits its ability to represent statistical variation. But the TT Series measurement data reflects a cumulative representation of multiple samples produced during that phase. This distinction helps explain the minor deviations observed and highlights the need for multi-part scanned data in future compliant modeling efforts to better capture part-to-part variation results.

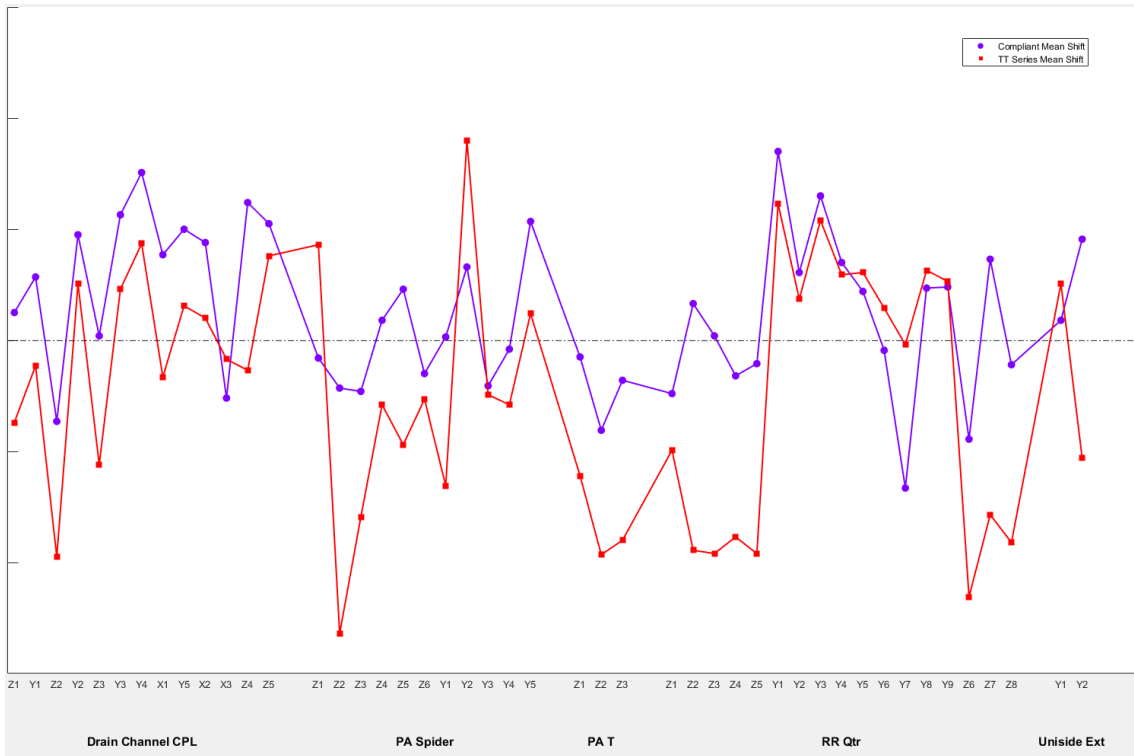


Figure 4.8: Mean Shift of Compliant Model & TT Series Production

Running Production & TT Series Mean Shift

When comparing the TT series data with the current running production as shown in the Fig. 4.9, it is evident that the process adjustments observed during the TT series continue to be reflected in the ongoing production. This consistency suggests that the adjustments made during that period have been standardized and integrated into the current assembly practices. While these adjustments were not originally part of the formal design intent, they have been adopted in the assembly process as the most

4. Results

effective compromise to achieve acceptable overall quality within the given constraints. Further insights into these adjustments were gathered through detailed interviews with the production team, as discussed in Section 4.5. Their input helped clarify the rationale behind these process changes and confirmed that they continue to be followed consistently in the running production environment. A detailed trend plot for all three mean shifts has been presented in the Appendix A.4.

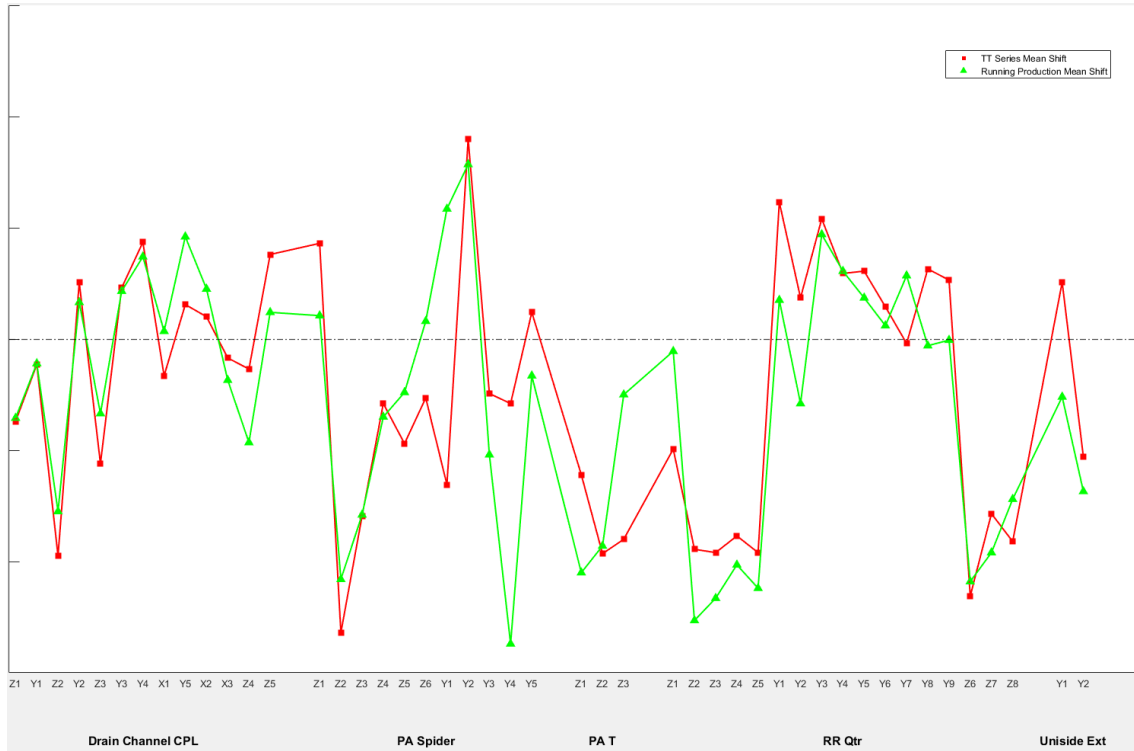


Figure 4.9: Mean Shift of Running Production & TT Series Production

Y Direction MPs

The Y-direction measurement points serve as the primary datum reference on the whole BSC Assembly. As the plot in Fig. 4.10, all the PAs effectively capture the process variation within the 8σ spread predicted by the simulation model except for the PA Spider. Also, the mean shift from the compliant model follows along with the production mean shift, which shows a good prediction behaviour of the compliant model. These findings directly inform the root cause analysis discussed in Section 4.5 and support the optimization strategies.

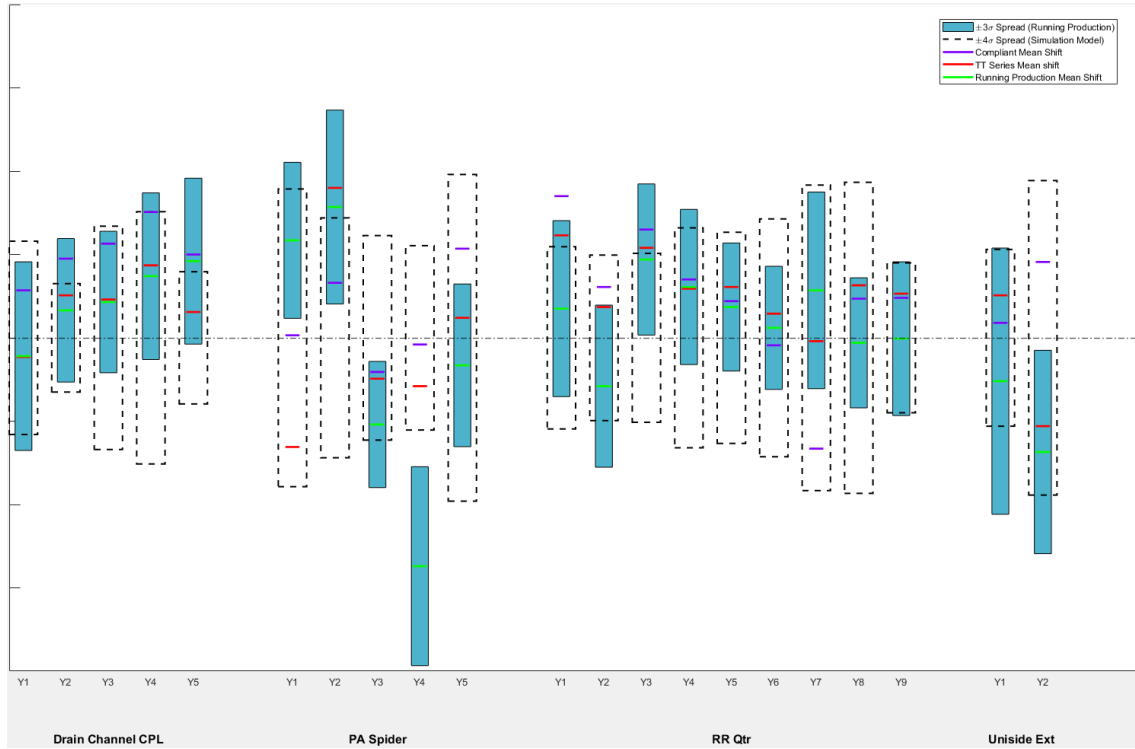


Figure 4.10: Y Direction Measurement points Interval plot

Z Direction MPs

In the Z-direction, the measurement points across all pre-assemblies tend to shift toward the negative side of the plot, as shown in Fig. 4.11. This consistent trend indicates that the rigid simulation model is unable to capture the process effects within the 8σ spread limits fully. Also, the compliant model is not effective in following the mean shift. Such deviation suggests that either of the simulation inputs does not accurately reflect real-world conditions.

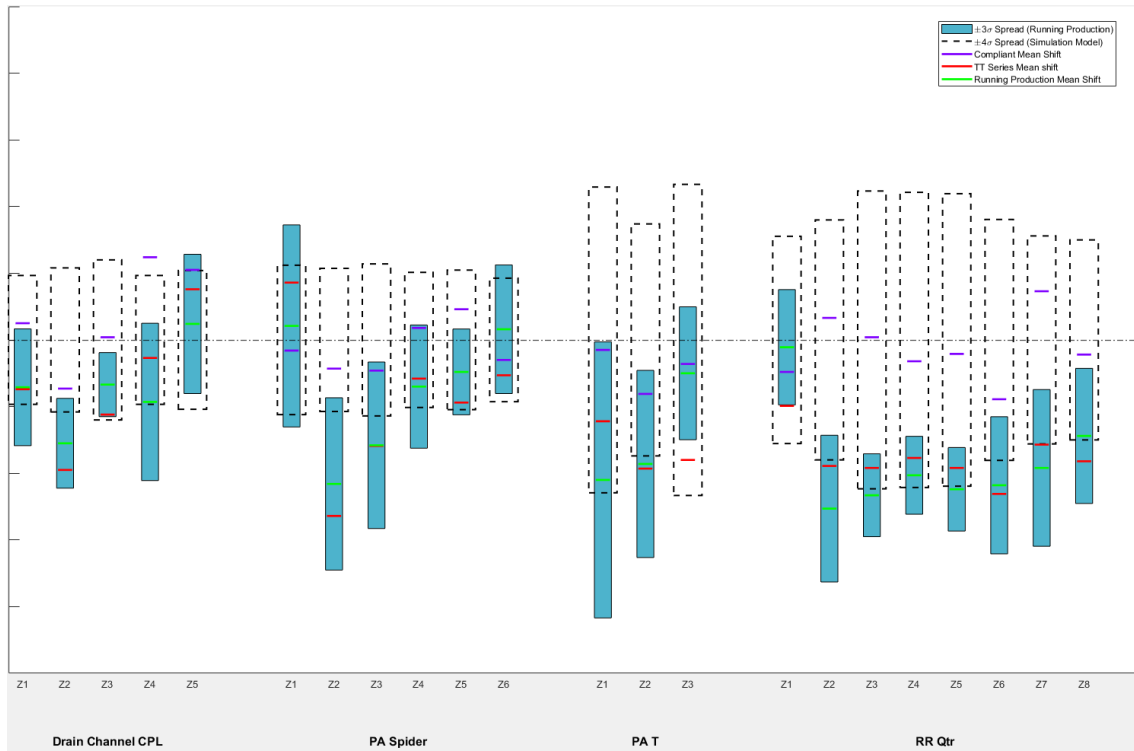


Figure 4.11: Z Direction Measurement points Interval plot

X Direction MPs

In the X-direction, only three measurement points are present, all of which come under the PA Drain Channel. Both the rigid and compliant simulation models accurately capture the process effects at these points, demonstrating a strong correlation with the real-world measurement data as shown in Fig. 4.12.

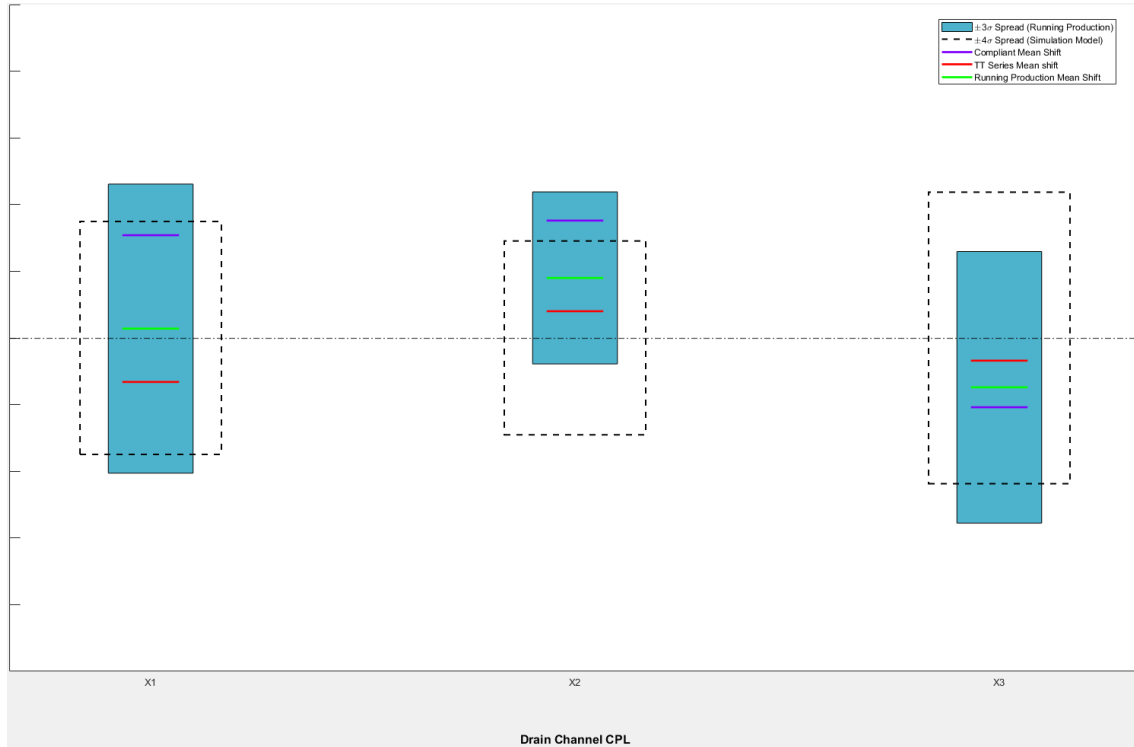


Figure 4.12: X Direction Measurement points Interval plot

4.4 In-depth Interviews

Based on all the data collected and plots generated, the in-depth interviews were conducted with the same engineers who were interviewed before. A total of three interviews were conducted by showing them all the results and discrepancies found within the data. The presentation was made in such a way as to discuss the results one by one, covering each pre-assembly. This method has been enhanced and is open to discussion, making it easier to understand the variations within production. As discussed before, within all the plots, there were so many process effects that were going down towards the negative side of the plot. To find these factors, Root cause analysis was conducted through the discussion and reasons explained by the Manufacturing Engineer (ME).

ME described all the process adjustments that have been made within the process of the BSC assembly at the Charleston plant. The important insights regarding the measurement practices were also explained in detail. The measurement fixture used for the BSC assembly in the inline measurement follows the reference locating system defined in the official documentation. In this setup, the whole BSC assembly

is laid down on the fixture and measured, which means the gravity will be a minimal contributor. But the offline measurement using CMMs is performed in car coordinates, where the complete assembly is stationed as it would be in the actual vehicle structure. To ensure the measurement consistency, the correlation between the inline and offline systems is maintained, and this alignment is verified two or three times per year. This observation was very important, and it helped to update the gravity direction within the compliant simulation model. Based on the updates, the adjustments were made to the compliant model, improving the accuracy and strengthening the correlation with real-world measurement data.

GE1 discussed the compliant model and told the plots are capturing the mean shift of the model effectively. The lack of an updated model for comparison was also emphasized, as developing one is very complex and time-consuming.

GE2 provided further insights and explained more about the structural design of the BSC assembly, emphasizing the complexity within the whole BIW Process. BSC assembly serves as the important structure and critical sections to manage from a geometry assurance perspective. GE2 also discussed the concept issues of some PA parts and the PA spider variation.

4.5 Root cause Analysis

In this section, the main process deviations and variations between rigid, compliant, and measurement data have been discussed. These process deviations were identified through a detailed analysis of the correlation study for individual measurement points and an in-depth interview discussion with *ME* from the Charleston plant.

4.5.1 PA RR Qtr

In the Y-direction, all MPs are within the defined limits as shown in the Fig. 4.10. Additionally, the mean shift from the compliant analysis closely follows the production mean shift, which shows a high level of model accuracy. However, in the Z-direction, all MPs are noticeably shifting toward the negative side of the plot, as shown in the Fig. 4.11. During interviews with the production team, it was said that this deviation is due to a known gap issue between the roof frame and the Body Side Outer (BSO). To compensate for this misalignment during assembly, the RR Qtr component is positioned lower, which is reflected in the measurement data. The process adjustment within the PA RR Qtr is illustrated and shown in the Fig. 4.13.

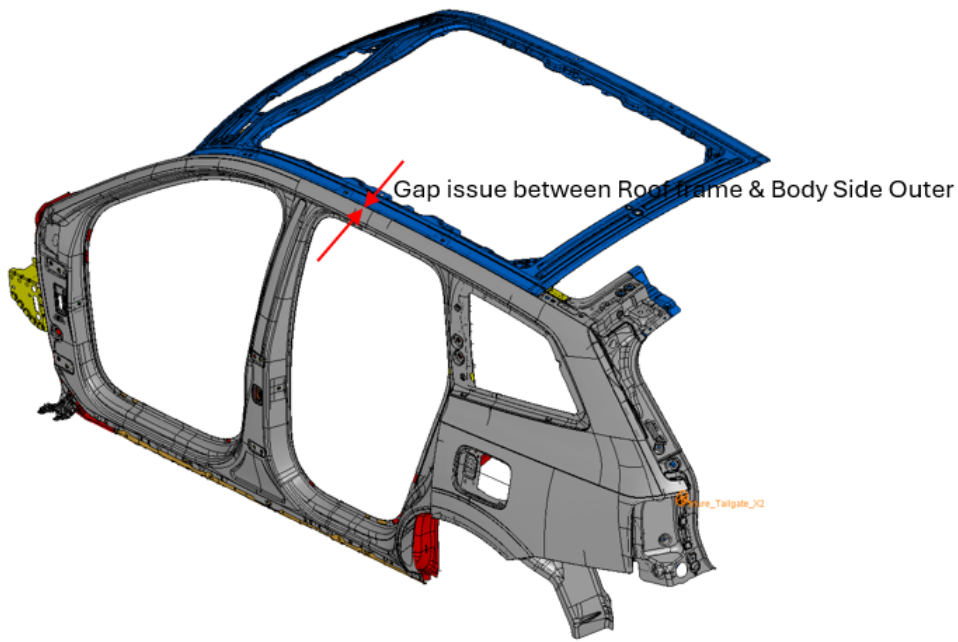


Figure 4.13: Illustrating the process adjustment in PA RR Qtr

4.5.2 PA Drain Channel

In the Y-direction, as shown in the Fig. 4.10, the MPs are well aligned across both the rigid simulation and the compliant analysis, closely following the trends observed in the TT series and current production data. This indicates a good correlation and consistent behavior across datasets. However, in the Z-direction, the variation mirrors that seen in the RR Qtr pre-assembly as shown in the Fig. 4.11. This is primarily due to the same gap issue identified between the roof frame and the BSO. A similar process adjustment has been applied here as well, lowering the part slightly to compensate for the misalignment during assembly. Additionally, the X-direction measurement points, which are located within the Lamp Panel section as shown in the Fig. 4.12, show no significant variation. Both the rigid simulation and compliant analysis effectively capture these points well within the acceptable limits, indicating stable process behavior and high accuracy in simulation results for this direction. The process adjustment within the PA Drain channel is illustrated and shown in Fig. 4.14.

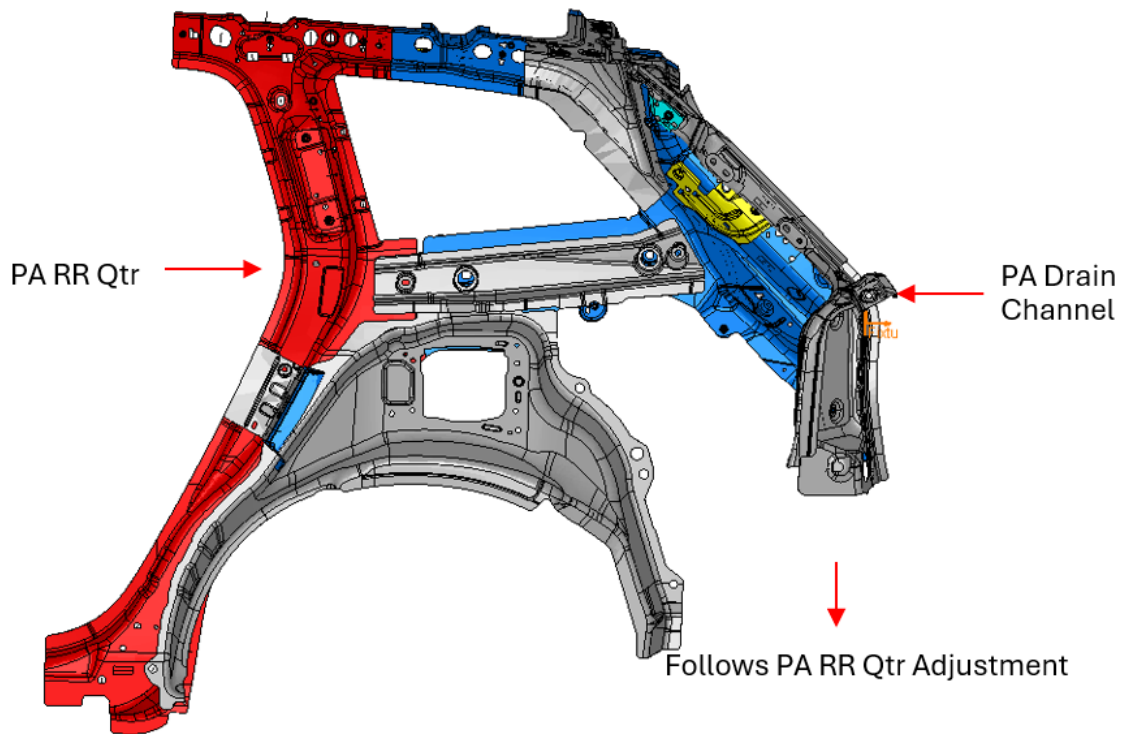


Figure 4.14: Illustrating the process adjustment in PA Drain Channel

4.5.3 PA Spider

In the Spider pre-assembly, significant variation is observed in both the Y and Z direction MPs, which are not accurately captured by either simulation model as shown in the Fig. 4.10 & 4.11. A key contributor to this discrepancy is the shift in the Y7 clamping locator position between BSI Step 2 and BSC CPL, which is illustrated in Fig. 4.15, leading to localized warping in the A-pillar lower and sill outer regions. Additionally, ME also mentioned that the absence of sufficient clamps or supports in the front region further amplifies the variation.

In the Z direction specifically, all the MPs are located on the A-pillar Reinforcement Upper—a long and flexible part, highly prone to deformation. The major issue here lies in the difficulty of adapting the single-part reference system used in the simulation to represent behavior at the full assembly level. Although part-level measurements remain within limits, significant variations are seen during final assembly due to this adaptation issue.

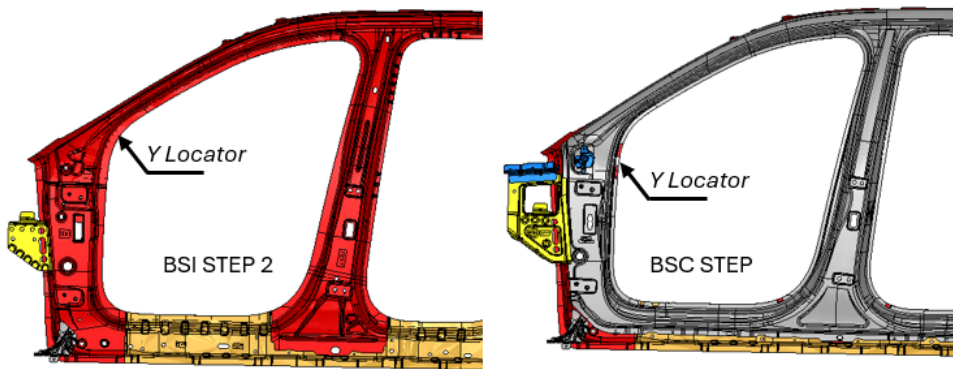


Figure 4.15: Illustrating the clamp locator shift in PA Spider

4.5.4 PA T

In the PA T assembly, only Z-direction MPs are available as shown in the Fig. 4.11, all located on the A-pillar Extension component. The variation observed here closely mirrors that of the Spider pre-assembly, which is expected as PA T is positioned between the BSO and the PA Spider sub-assemblies. Moreover, there is also a concept-related issue with the A-pillar Extension. It does not align properly within the overall assembly, and hard to control the angle, further contributing to the observed variation. The process adjustment within the PA T is illustrated and shown in Fig. 4.16.

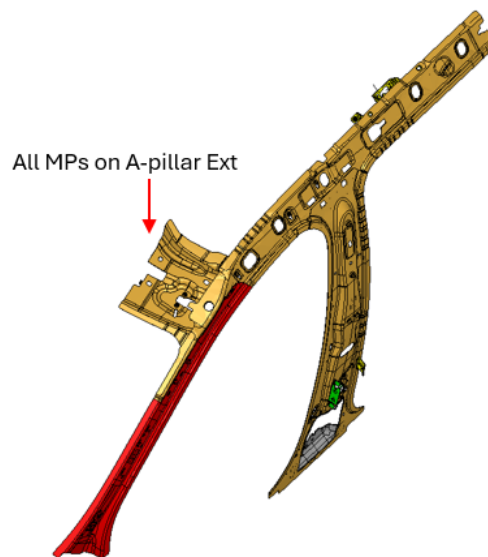


Figure 4.16: Illustration of variations on PA T

4.5.5 Uniside Ext

For the Uniside Ext part, only two MPs were available for analysis as shown in the Fig. 4.10. Among them, one point showed a noticeable shift towards the negative side. This deviation can be attributed to the fact that, at the BSC assembly level, the Uniside part is supported but not clamped, leading to instability and allowing minor

shifts during assembly, which result in increased variation. The area with no clamps within the Unside Ext is illustrated and shown in Fig. 4.17.

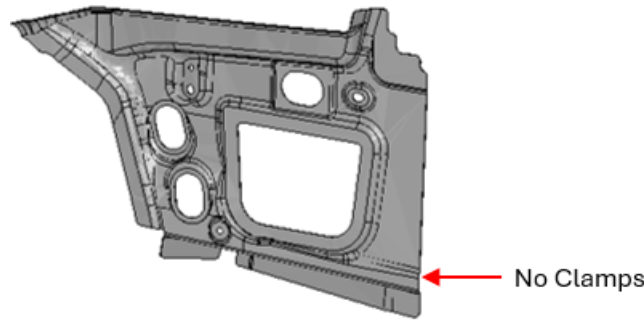


Figure 4.17: Illustrating the lack of clamps on Unside Ext

4.6 Optimization

After identifying key discrepancies between the simulation and measurement data through the initial correlation studies, it became clear that the rigid simulation model required refinement to better reflect actual production conditions. The goal of the optimization process was to minimize these discrepancies by adjusting critical input parameters such as the locating system, reference point definitions, and tolerance stack-ups within the RD&T software.

This phase was guided by the findings from the root cause analysis, expert interviews, and insights gained from comparing both rigid and compliant models. By iteratively modifying the simulation setup and validating each change against production data, the model was updated and optimized for higher accuracy and reliability.

Although the compliant model provided valuable insight into part deformation behavior, it was not considered for optimization due to its complexity and the limited experience available in handling it. Therefore, all optimization efforts were focused on enhancing the rigid simulation model, which served as the foundation for improving prediction accuracy and enabling more dependable early-phase geometry assurance decisions.

4.6.1 Rigid Simulation Model Optimization

The final and most critical phase of this work involved a focused effort to optimize the rigid simulation model. As is widely known within geometry assurance, optimization in rigid simulations primarily depends on two foundational elements: establishing an effective positioning system and accurately defining the tolerance range and C_p values to reflect and control variation appropriately.

4. Results

With insights from the interviews and the supervisor, the optimization process began by thoroughly exploring the model structure, from individual parts to the full Body Side Complete (BSC) assembly. The positioning systems used across various parts and sub-assemblies were reviewed in detail to understand the logic behind their definitions. Based on this understanding, several modifications were tested on the locator definitions to enhance the robustness of the model. However, it became evident that these adjustments did not always give the expected improvements. So, in some cases, the variation even increased, highlighting the complexity and sensitivity of the model. As a result, the focus shifted toward the final stages of the assembly process, specifically BSI Step 1, BSI Step 2, and BSO. These stages are particularly important as they closely reflect the conditions and configurations used in the actual measurement fixture. To better align the simulation with the real-world process, alternative assemblies were defined for these final steps. This strategy proved effective, significantly reducing simulation variation and improving the overall correlation with measurement data.

The alternative assembly in the tolerance analysis refers to a modified configuration of the positioning system that could better reflect the actual physical assembly setup. These are created for the same part or sub-assembly by redefining the positioning system to achieve better correlation. This allows greater impact and flexibility to achieve a positioning system similar to reality. Especially within the rigid simulation, a part or sub-assembly can only be constrained using the 3-2-1 approach, making it difficult to achieve better variation results. However, the alternative assemblies reduce this impact and can achieve better results without compromising the overall structure.

By concentrating on these critical final stages and aligning the model setup more closely with the physical assembly and measurement approach, the optimization led to better improvements in simulation accuracy and predictive capability as shown in the Fig. 4.18.

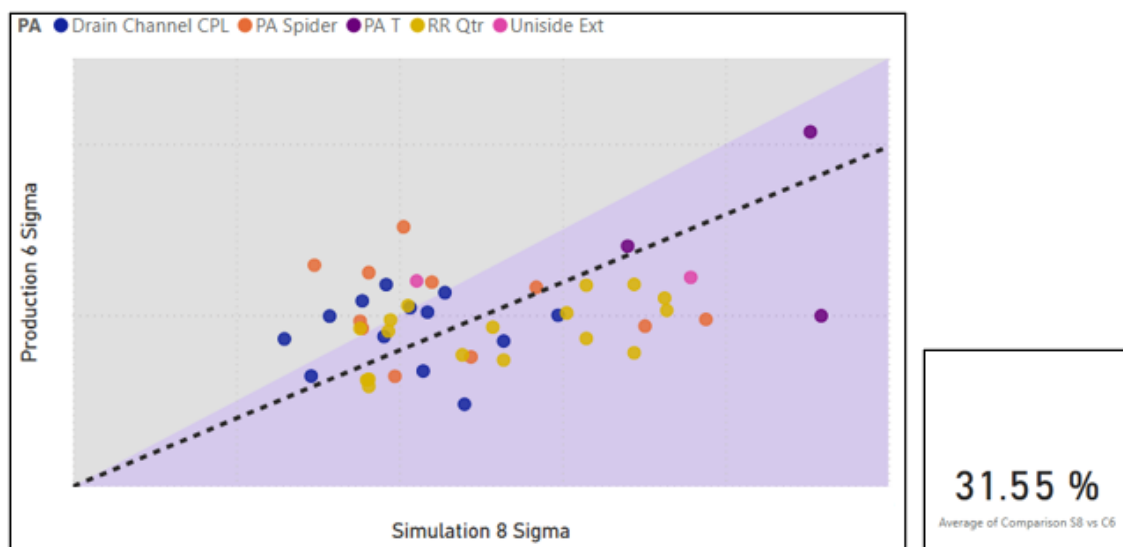


Figure 4.18: Scatter plot after rigid model optimization

4.6.2 Simulation Guidelines

While specific simulation guideline details, such as locating schemes and alternative assemblies within the rigid simulation model, are not disclosed due to confidentiality. This section outlines key general considerations that emerged as crucial during the optimization of the rigid simulation model for the BSC Assembly. The objective of these guidelines is to provide a structured approach for developing accurate rigid simulation models across different PAs within BIW structures. The following considerations should be adopted as foundational principles when setting up and evaluating rigid simulations:

A. Defining a proper Positioning system

A clearly defined locating and reference system is foundational in rigid simulation. Each part or sub-assembly must be accurately constrained using the appropriate 3-2-1 locating system strategy. The reference system should be consistent with that used in the physical measurement setup to avoid misalignments during correlation. Additionally, the reuse of locator points occurs as the part progresses from one assembly stage to the next level. This defines how the individual parts and sub-assemblies are positioned and constrained together, making it closer to the real-world positioning system.

B. Part Mating

When developing the rigid simulation model, it is essential to carefully define how individual parts are connected during the assembly process. These mating definitions should be properly selected to reflect how parts are positioned and assembled in reality conditions. Choosing appropriate part-to-part mating not only ensures correct alignment within the specific pre-assembly but also helps maintain that alignment as the assembly progresses to higher levels. If part mating is poorly defined or inconsistent with the actual assembly reference, it can introduce unintended variation or instability into the simulation results. This may lead to higher variations and excessive build-up of errors across the assembly. By contrast, selecting the locating points of the parts to mate strategically and determining the order creates a more stable simulation structure, which improves overall predictive accuracy. In summary, proper part mating should be treated as an important step in model setup. It plays a key role in controlling variation, supporting traceability, and ensuring that simulation behavior aligns closely with real-world assembly conditions.

C. Whole Assembly Level

To accurately simulate geometric behavior, the complete sub-assembly must be properly guided and referenced at the full assembly level. Instead of relying on lower-level or localized locating schemes, the simulation model should reflect how the complete assembly is supported and constrained during production. This approach helps to capture the cumulative variation effects and also ensures that the final developed model represents the influence of higher assembly steps.

D. Alternative Assembly specified within MPs

To ensure proper comparison between simulation results and real-world measurements,

all MPs must be represented at the appropriate assembly level, particularly when alternative assemblies are used. In many cases, specific parts or sub-assemblies may be better constrained and represented within an alternate assembly setup, rather than the main build sequence. Alternate assemblies are created in the simulation environment to better reflect real-world conditions by adjusting the positioning system. When these are used, any associated MPs must also be reassigned and updated within the context of the alternate assembly. This includes assigning the MP to the correct reference system of the part and ensuring that the assembly follows the same logic as reality. If these updates are not done, it would lead to discrepancies in variation results, misinterpretation of data, or incomplete correlation with physical measurements.

E. Master PMI

All simulation inputs, like tolerances, ranges, and datums, should be derived from the latest validated master Product Manufacturing Information. This alignment avoids inconsistencies that can arise from using local or outdated documentation. By updating the simulation setup in the master PMI, the model maintains consistency with design intent and production standards, supporting both internal review and digital validation processes.

4.7 Fish Bone Diagram showing key Contributors

Finally, a fishbone diagram was developed to systematically identify and categorize the potential contributors to geometrical variation within the BSC assembly. The primary objective of this diagram is to provide a structured overview of the factors influencing variation and assess their feasibility for inclusion within the different simulation models.

In the diagram 4.19, different colors are used to distinguish the level of consideration each factor receives in simulation modeling:

- Green indicates factors that can be effectively included and modeled within the rigid simulation environment in RD&T.
- Blue represents factors that can be modelled within the compliant simulation model.
- Red highlights factors that cannot be included in either simulation model.
- Yellow marks the factors that are possible to include in a compliant simulation model but were not incorporated in the compliant model developed within this thesis.

This classification not only clarifies the scope of simulation but also supports future efforts to expand and refine digital modeling practices for improved geometry assurance. A detailed fishbone diagram is presented in the Appendix A.5

4. Results

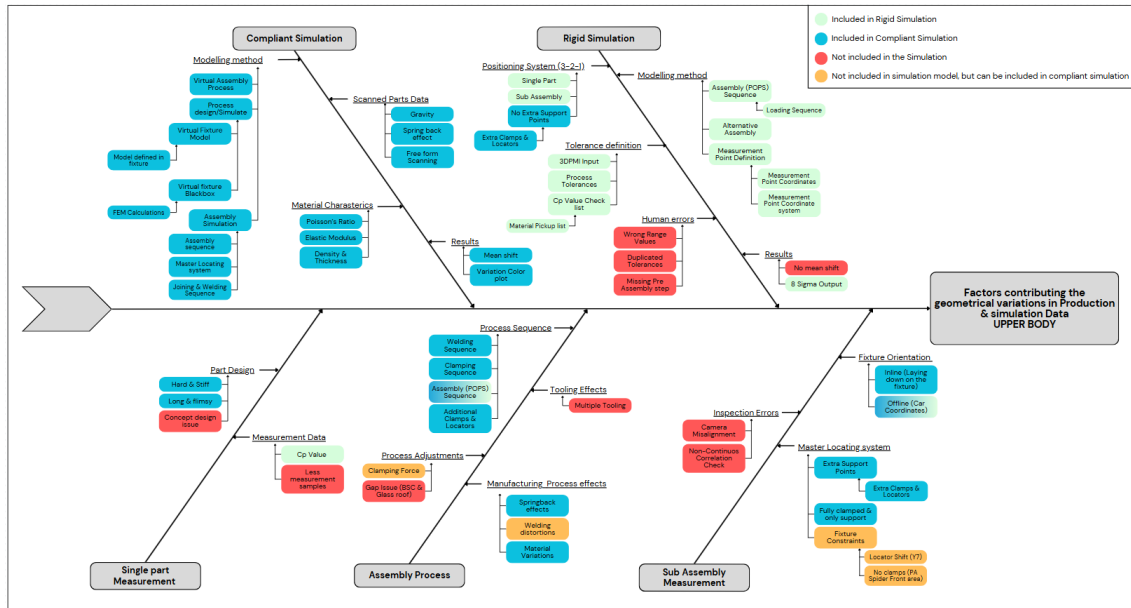


Figure 4.19: Fishbone Diagram showing the key contributors to geometrical variations

5

Discussion

This thesis study explored the various tolerance simulation models within BIW assemblies, using both rigid and compliant analysis techniques. The importance of geometry assurance is rising day by day with the increasing competition and demand for quality within the automotive industry. While simulation tools like RD&T offer strong predictive capabilities, their effectiveness highly depends on the model's actual behavior and constraints.

A key takeaway from the study was the identification of various contributors to geometrical variations in BIW assemblies. These include modelling inaccuracies and limitations in the current simulation modelling strategies. According to the comparison findings and expert interviews, it is demonstrated that a rigid simulation model can offer the variation results closer to reality when it is defined and developed properly by proper tolerance and positioning systems allocation. The compliant model, even though developed with the single part scanned data, could rely on the comparison since it closely follows the measurement data, and this analysis can pose challenges in computational time and complexity to develop the model through inadequate experience.

The fishbone diagram developed during this study has helped in categorizing the contributors, specifically distinguishing the factors that can be included within the simulation model and the ones that cannot be included. Factors such as the assembly sequence are very critical and must be accurately represented in both rigid and compliant simulation models to ensure realistic outcomes. However, factors such as multiple tooling effects introduce numerous probabilities, making them difficult to incorporate into simulation models. Another significant factor is the clamping force and welding distortions, which can be effectively accounted for in the compliant analysis. These factors will have a substantial impact on the final geometry of assembled parts, and they were not included in the compliant model developed for this study. Incorporating these factors would bring the simulation much closer to the actual process variations, enhancing its predictive accuracy.

The compliant model was developed using the scanned part data from November 2022, and the relevance of this model is limited as it is an old model and is based on a single scanned part data. As a result, it does not capture part-to-part variation to reflect the current state of production variations. Moreover, this can only provide mean shift values and not the statistical variation parameters. In contrast, the rigid analysis provides the statistical parameters and cannot reflect the mean shift because it

operates under idealized assumptions that all parts are stiff bodies in this environment.

In summary, the methodology adopted in the thesis allowed for iterative improvement of the simulation model, starting with the expert interviews and determining root cause analysis for each PA. Although the compliant model could not be optimized due to its complexity and time constraints, it provided valuable insights into BSC assembly behaviour, continuing this study in future work.

5.1 Research Questions

In the following section, the two research questions presented in Section 1.3 are revisited. The corresponding findings are carefully analyzed and discussed to provide clear and thoughtful answers to each question.

5.1.1 RQ-1

The first research question is formulated as:

How do different modelling strategies affect accuracy and model complexity for sheet metal assemblies?

This thesis evaluated two simulation modeling methods, rigid and compliant modeling, for their effectiveness in predicting geometrical variation within automotive BIW assemblies. The rigid simulation model was optimized through multiple improvements like updating Cp values, removing duplicated tolerances, and aligning alternative assemblies. These improvements demonstrated a significant improvement in correlation with the measurement data. It also provided accurate and statistical outputs such as sigma and Cp values, which makes it highly suitable for early-phase design verification and robust tolerance stack-up analysis. But the rigid models inherently lack mean shift representation due to their idealized assumption of undeformed parts, which limits their ability to reflect real-world process variations. Within the compliant simulation model, mean shifts are achieved by simulating part flexibility and physical distortion due to clamping and joining forces. This analysis offers a more realistic view of part behavior. The model's reliability on single-part scanned data, particularly in the model used for this study, has limited the statistical validity. Additionally, the model's complexity made it less suitable for iterative development within the scope of this thesis.

5.1.2 RQ-2

The second research question is formulated as:

What factors contribute to variations in sheet metal assemblies, and how can they be effectively modeled in simulation methods?

The study also identified and categorized several contributors to geometrical variation through creating a fishbone diagram, such as locating system, tolerance input accuracy, assembly sequence, clamping forces, and part deformation. Some factors, like assembly

sequencing and Cp input quality, could be effectively modeled within both rigid and compliant frameworks. The other factors, like multi-tooling effects or unexpected part warping, will be difficult to simulate due to their unpredictability and variability. The root cause analysis, along with expert interviews and correlation studies, supports that the modeling accuracy does not always depend on software capabilities, but also on the alignment with real process conditions. Finally, a hybrid approach is recommended, where both the rigid and compliant simulations are considered for each PA to find out the critical areas of variation and balance the strategy for simulation efficiency and real-world assembly behaviour.

6

Conclusion

This master's thesis is mainly focused on exploring and enhancing the accuracy of tolerance simulation models by performing a comprehensive correlation study between real-world measurement data and simulation results within the BSC Assembly. This study is motivated by the need for predictive accuracy in simulation models, especially when dealing with rigid and non-rigid models. This also helped to identify the key contributors to the geometrical variations within the BSC Assembly.

The most important finding is the difference between the rigid simulation model data and the measurement data. Through proper analysis, it was found that the accuracy of rigid simulations can be significantly improved by implementing alternative assembly configurations and refining tolerance inputs. The introduction of realistic single-part Cp values and the elimination of process tolerances have shown measurable improvements in correlation accuracy. The compliant model is mainly dependent on the scanned parts data, highlighting the potential mean shift, and also follows the real-world measurement data closely. However, the broader application of compliant modeling is currently limited by its complexity to develop, longer time, and specialized expertise.

Beyond model comparison, this thesis also identifies the specific root causes in the key sub-assemblies within the BSC Assembly, identifying the specific contributors to geometrical variations. Findings such as the process adjustments, like the clamping locator shift and lack of support or clamps, played an important role in the optimization of the rigid simulation model. These results emphasize the value of following standardized procedures for simulation model development, which include the integration the optimization techniques, continuous measurement data feedback, and formulating the simulation guidelines that bridge the gap between the rigid simulation model with reality. This study methodology can be further taken as a reference for future BIW Platforms to develop robust simulation models. The non-rigid models are becoming more accessible, there is an immense potential to integrate them early in the design phase, even before production starts. For further development, the compliant model can be developed by multiple scanned parts to obtain the statistical variation data that could enhance the reliability of these models.

In conclusion, this thesis successfully achieves its objective of enhancing tolerance simulation accuracy through data-driven optimization. The proposed simulation improvements, root cause insights, and recommended guidelines serve as steps toward a more predictive, reliable, and efficient BIW tolerance simulation framework.

Bibliography

- [1] Chatgpt. *Open AI*. 2025. URL: <https://openai.com/chatgpt/overview/>. Accessed: [250715].
- [2] R. Söderberg, L. Lindkvist, K. Wärmefjord, and J. S. Carlson. “Virtual geometry assurance process and toolbox”. In: *Procedia Cirp* 43 (2016), pp. 3–12.
- [3] Wikipedia. *Volvo Cars*. 2025. URL: https://en.wikipedia.org/wiki/Volvo_Cars. Accessed: [250404].
- [4] H. Zheng, F. Litwa, M. Bohn, and K. Paetzold. “Tolerance optimization for sheet metal parts based on joining simulation”. In: *Procedia Cirp* 100 (2021), pp. 583–588.
- [5] M. Koumas, P. E. Dossou, and J. Y. Didier. “Digital transformation of small and medium sized enterprises production manufacturing”. In: *Journal of Software Engineering and Applications* 14.12 (2021), pp. 607–630.
- [6] R. Söderberg, K. Wärmefjord, J. S. Carlson, and L. Lindkvist. “Toward a Digital Twin for real-time geometry assurance in individualized production”. In: *CIRP annals* 66.1 (2017), pp. 137–140.
- [7] F. Wandebäck. *Geometry simulation of tolerance requirements*. 2023. URL: <https://www.ri.se/en/expertise-areas/services/geometry-simulation-of-tolerance-requirements>. Accessed: [2025-01-28].
- [8] K. Wärmefjord, R. Söderberg, B. Lindau, L. Lindkvist, and S. Lorin. “Joining in nonrigid variation simulation”. In: *Computer-aided technologies-applications in engineering and medicine* (2016).
- [9] Volvo Cars. *Volvo XC90 body structure*. 2014. URL: <https://www.media.volvocars.com/global/en-gb/media/photos/148216/volvo-xc90-body-structure-without-text>. Accessed: [2025-04-21].

- [10] R. Söderberg, L. Lindkvist. *Computer Aided Assembly Robustness Evaluation*. 1999. URL: <https://www.tandfonline.com/doi/epdf/10.1080/095448299261371?needAccess=true>. Accessed: [2025-04-20].
- [11] K. Wärmefjord, J. Hansen, and R. Söderberg. “Challenges in geometry assurance of megacasting in the automotive industry”. In: *Journal of Computing and Information Science in Engineering* 23.6 (2023), p. 060801.
- [12] B. Schleich, K. Wärmefjord, R. Söderberg, and S. Wartzack. “Geometrical variations management 4.0: towards next generation geometry assurance”. In: *Procedia CIRP* 75 (2018), pp. 3–10.
- [13] V. Ramesh Sagar, S. Lorin, K. Wärmefjord, and R. Söderberg. “A robust design perspective on factors influencing geometric quality in metal additive manufacturing”. In: *Journal of Manufacturing Science and Engineering* 143.7 (2021), p. 071011.
- [14] K. Wärmefjord. *Variation control in virtual product realization-a statistical approach*. Chalmers Tekniska Hogskola (Sweden), 2011.
- [15] Enventive Engineering. *What are Worst Case, RSS and Monte Carlo calculation methods and when to use them in tolerance analysis?* 2023. URL: <https://enventive.com/tolerance-analysis-resources/worst-case-rss-and-monte-carlo-simulation-calculations-for-tolerance-analysis/>. Accessed: [2025-04-29].
- [16] Smlease Design. *Tolerance Stackup Analysis: Worst Case and RSS*. 2019. URL: <https://www.smlease.com/entries/tolerance/tolerance-stackup-analysis/>. Accessed: [2025-04-29].
- [17] H. Yan, X. Wu, and J. Yang. “Application of monte carlo method in tolerance analysis”. In: *Procedia CIRP* 27 (2015), pp. 281–285.
- [18] B. Schleich and S. Wartzack. “Novel approaches for the assembly simulation of rigid skin model shapes in tolerance analysis”. In: *Computer-Aided Design* 101 (2018), pp. 1–11.
- [19] P. Franciosa. *Modeling and Simulation of Variational Rigid and Compliant Assembly for Tolerance Analysis*. 2009. URL: https://www.researchgate.net/publication/265643003_Modeling_and_Simulation_of_Variational_Rigid_and_Compliant_Assembly_for_Tolerance_Analysis. Accessed: [2025-04-30].

- [20] H. Zheng, F. Litwa, B. Reese, C. Li, M. Bohn, and K. Paetzold. “A modeling approach for elastic tolerance simulation of the body in white hang-on parts”. In: *Proceedings of the Design Society: International Conference on Engineering Design*. Vol. 1. 1. Cambridge University Press. 2019, pp. 3461–3470.
- [21] *Tolerance Simulation of Compliant Sheet Metal Assemblies Using Automatic Node-Based Contact Detection*. Vol. Volume 14: New Developments in Simulation Methods and Software for Engineering Applications. ASME International Mechanical Engineering Congress and Exposition. 2008, pp. 35–44. DOI: 10.1115/IMECE2008-66344. URL: <https://doi.org/10.1115/IMECE2008-66344>.
- [22] B. Lindau, K. Wärmefjord, L. Lindkvist, and R. Söderberg. “Virtual Fixturing: Inspection of a Non-Rigid Detail Resting on 3-Points to Estimate Free State and Over-Constrained Shapes”. In: *ASME International Mechanical Engineering Congress and Exposition*. Vol. 84492. American Society of Mechanical Engineers. 2020, V02BT02A065.
- [23] RDT Technology. *The tool RDT*. 2025. URL: <https://rdnt.se/software-tool/>. Accessed: [2025-04-30].
- [24] O. Wagersten. *Visualizing the effects of geometrical variation on perceived quality in early phases*. Chalmers Tekniska Högskola (Sweden), 2013.
- [25] K. Wärmefjord, R. Söderberg, A. Dagman, and L. Lindkvist. “Geometrical variation mode effect analysis (GVMEA) for split lines”. In: *Procedia CIRP* 92 (2020), pp. 94–99.
- [26] Quality Gurus. *Process Capability and Performance (Cp, Cpk, Pp, Ppk, Cpm)*. 2025. URL: <https://www.qualitygurus.com/process-capability-and-performance-cp-cpk-pp-ppk-cpm/>. Accessed: [2025-01-28].
- [27] Zeiss. *ZEISS Inline Measurement Technology*. 2025. URL: <https://www.zeiss.com/metrology/en/systems/optical-3d/automated-solutions/inline-inspection.html>. Accessed: [2025-05-04].
- [28] E. Kiraci, A. Palit, M. Donnelly, A. Attridge, and M. A. Williams. “Comparison of in-line and off-line measurement systems using a calibrated industry representative artefact for automotive dimensional inspection”. In: *Measurement* 163 (2020), p. 108027.
- [29] L. T. Blessing and A. Chakrabarti. *DRM: A design research methodology*. Springer, 2009.

- [30] Y. Zhang and B. M. Wildemuth. “Unstructured interviews”. In: *Applications of social research methods to questions in information and library science 2* (2009), pp. 222–231.

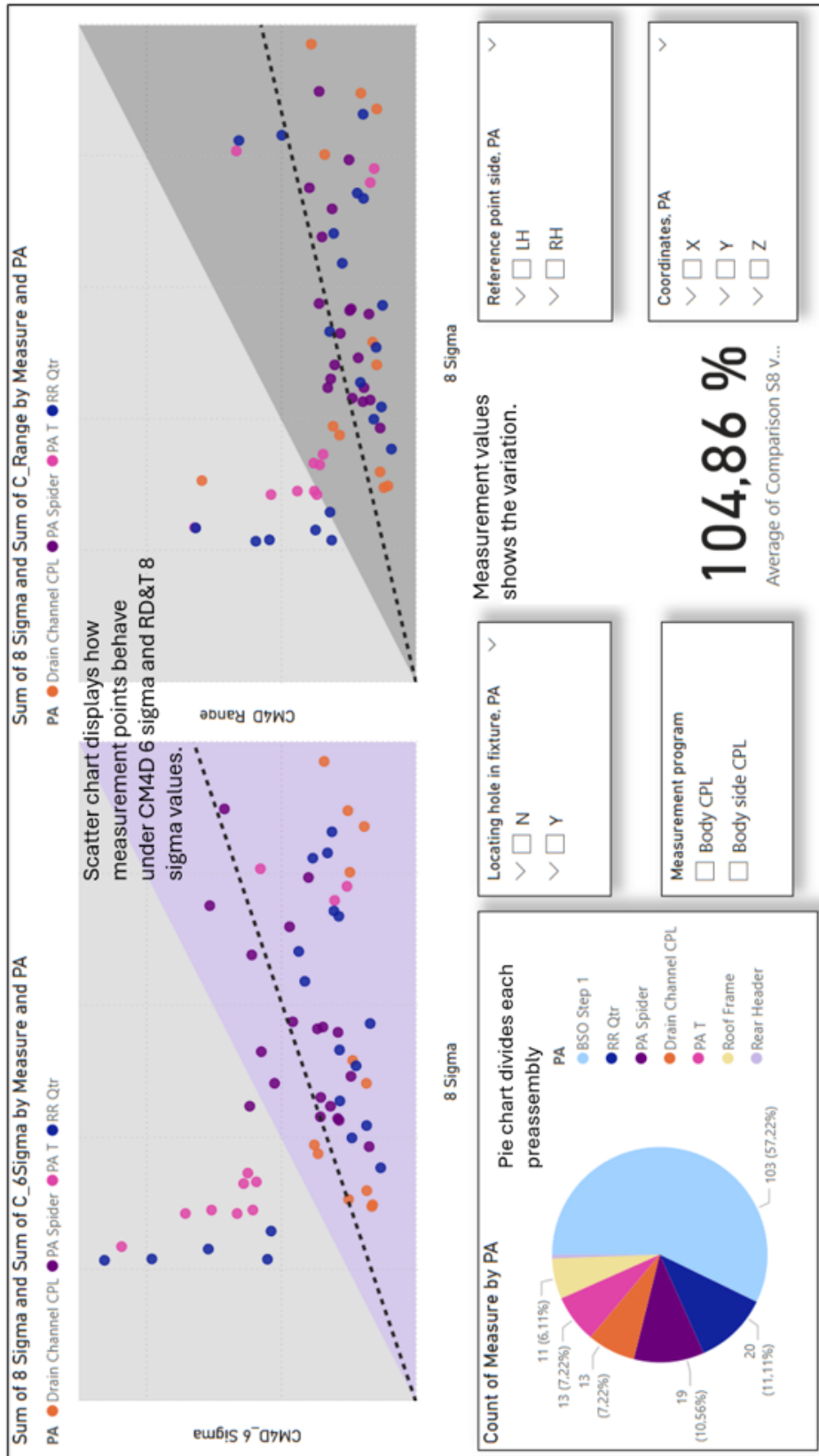
A

Appendix

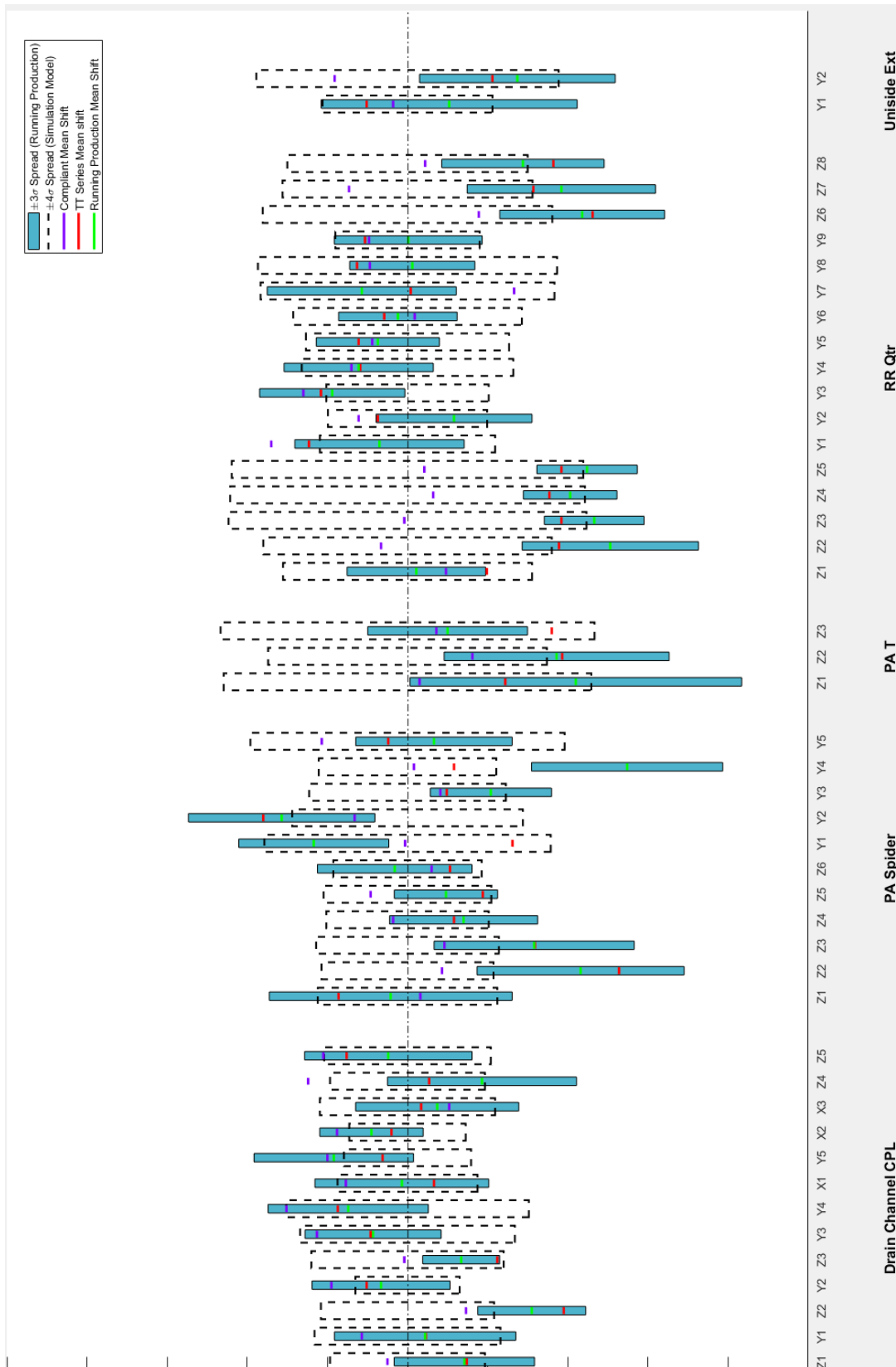
A.1 Initial Interview Questions

INITIAL INTERVIEW QUESTIONS	
Manufacturing Team Interview	
1	What are the major sources of variation in the assembly process that impact geometric tolerances?
2	What are the methods used to reduce process-level variations in production or assembly?
3	Is fixture change or loading part a major issue for variations? How will it be taken care of?
4	Any variations of the part that could start from the supplier end?
5	Any cases of process-level changes that have been useful in reducing these variations?
6	How can tolerance simulation models be better integrated with process-level data to maintain accuracy?
7	For some measurement points, we noticed abrupt jumps in the reading. How to handle this kind of data?
8	Any weld distortions that could effect the tolerances? How will it be handled?
Compliant Analysis Interview	
1	What are the differences between the Rigid body model and the Compliant model?
2	How are material properties and FEM method will be integrated into compliant model?
3	Which material properties will be considered, and also how process methods like joining or contact modelling will be integrated?
4	Is there any possibility to integrate both compliant and rigid body models as a single simulation model or method?
5	How complaint results are checked against production data?
6	Any recent improvements within these compliant models or simulation methods?
7	What are the major sources of variation in the assembly process that impact geometric tolerances?

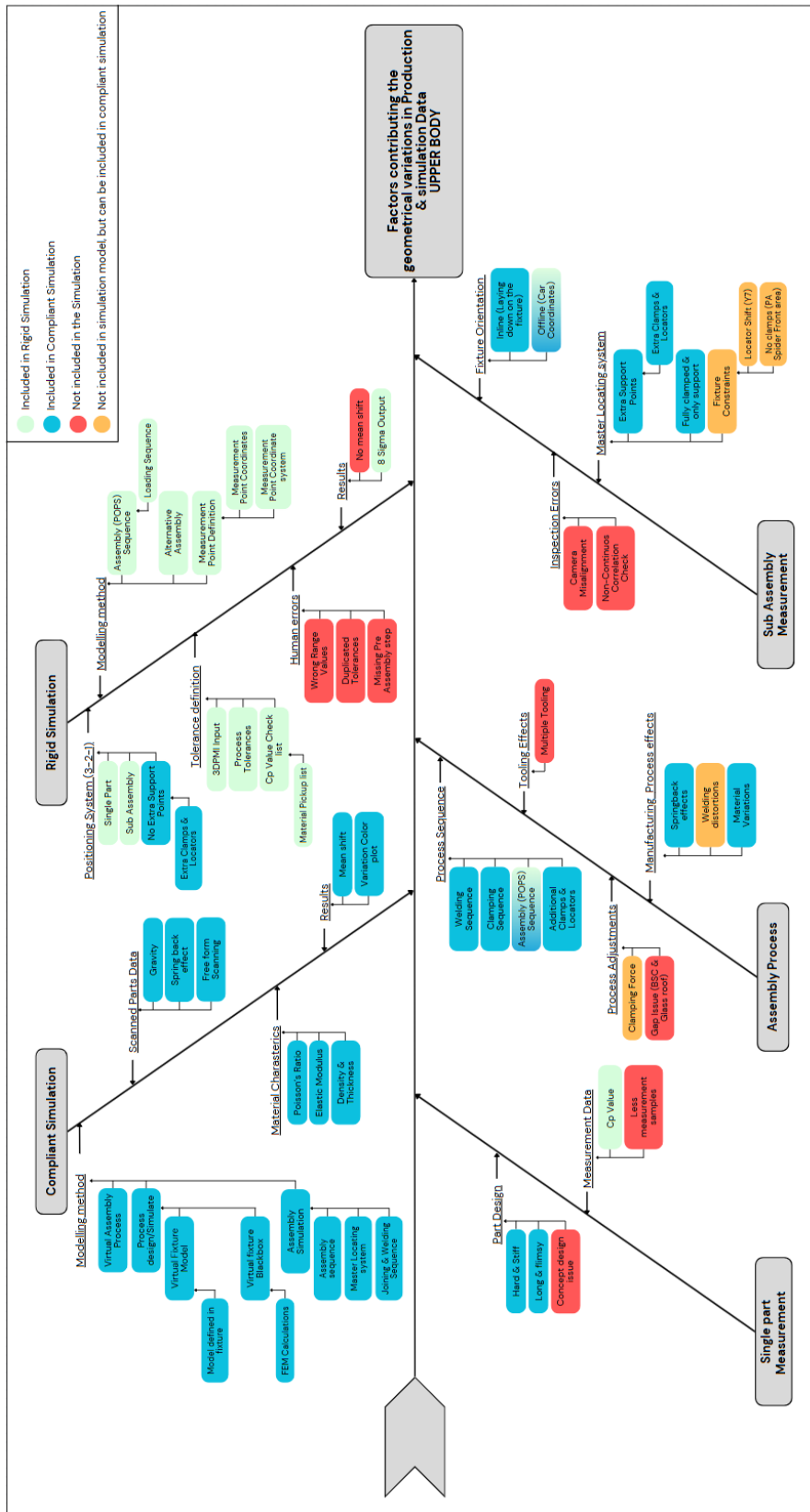
A.2 Interactive Plot created in PowerBI



A.3 Interval Plot with multiple mean shift



A.5 Fishbone Diagram



DEPARTMENT OF INDUSTRIAL & MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden

www.chalmers.se



CHALMERS
UNIVERSITY OF TECHNOLOGY