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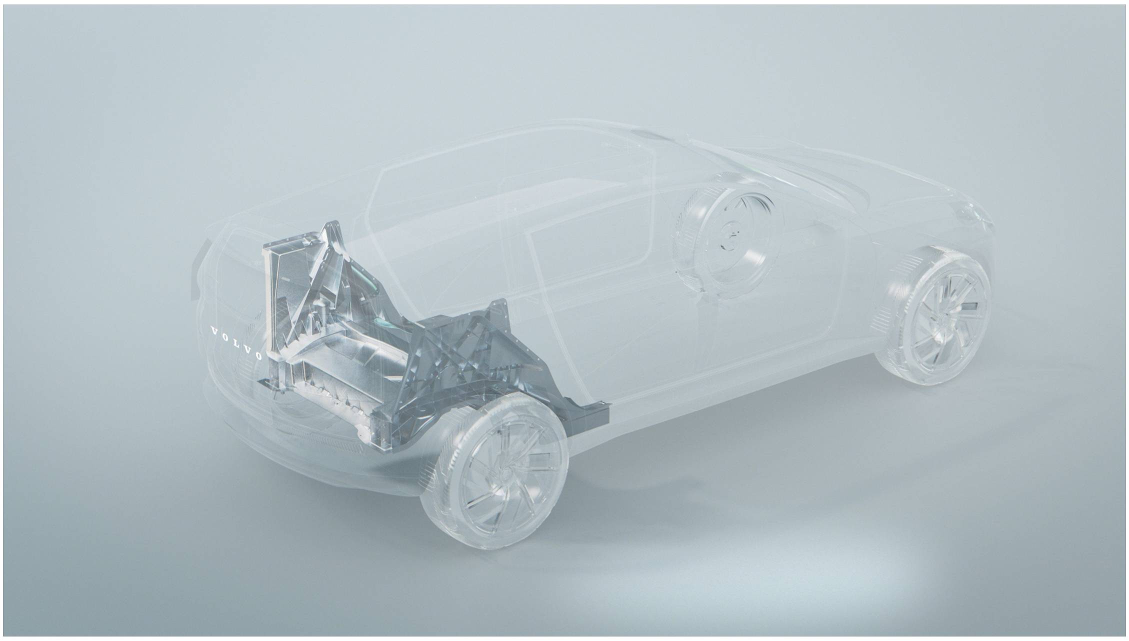

Cost Modeling of Geometrical Quality in Mega-cast Rear Floors

An evaluation of rear floor concepts, process improvements, and cost of geometrical quality

Master's thesis in Product Development

Alexander Haglund
Filip Cederqvist

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
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Abstract

This thesis investigates the geometrical quality of mega-cast rear floors in automotive manufacturing and its associated cost implications. The study has three main objectives: to evaluate and compare the geometrical quality of different rear floor concepts, to identify and assess methods for improving geometrical quality in mega-cast rear floors, and to develop a cost model that quantifies the cost of geometrical quality in mega-cast rear floors. A combination of statistical data analysis, literature review, expert interviews, simulation, and cost modeling was used to achieve these aims. Several statistical analysis tests were conducted to compare the geometrical quality of the different rear floor concepts. Further, a variety of methods and processes for improving the geometrical quality of the mega-cast rear floor was identified. Lastly, a cost model was developed to quantify the cost of geometrical quality for mega-cast rear floors. A separate simulation model was also set up to calculate costs arising from geometrical deviations and to serve as input for the cost model. The models were applied in different contexts including some of the most promising process improvements. The results of the applied methodology have provided insights into the importance of geometrical quality and its impact on cost. However, in some cases, a lack of data has introduced a degree of uncertainty into the results, making definitive conclusions difficult to draw. The methodology remains suitable for future use and is expected to yield clearer results as data quality improves.

Keywords: mega-casting, geometrical quality, cost modeling, high pressure die casing, cost simulation

Acknowledgements

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Alexander Haglund, Filip Cederqvist, Gothenburg, May 2025

List of Acronyms

Below is a list of acronyms that have been used throughout this thesis:

VCC	Volvo Cars Corporation
SPA	Scalable Product Architecture
HPDC	High-Pressure Die Casting
BIW	Body In White
CAT	Computer Aided Tolerancing
RD&T	Robust Design and Tolerancing
USL	Upper Specification Limit
LSL	Lower Specification Limit
MP	Measurement Point
Pp	Process Performance
ANOVA	Analysis of Variance
IQR	Interquartile Range
ABC	Activity-Based Costing
DES	Discrete-event Simulation

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1

Introduction

This chapter provides an overview of the project, giving an introduction to the topic of mega-casting, geometrical quality, and alternatives for geometrical quality improvements. Further, the aim of the project is specified along with its scope, limitations, and research questions. Lastly, the project is discussed from a societal, ecological, and ethical perspective.

1.1 Background

Volvo Cars Cooperation (VCC) has traditionally been producing floors by joining hundreds of sheet metal parts by welding, which was also the case for the first Scalable Product Architecture (SPA) platform, SPA1. Released in 2014, SPA1 included 100 parts for the rear floor. In 2022, VCC introduced the SPA2 platform which utilized a large casting part to replace multiple sheet metal parts and thereby reducing the total number of parts to 30. Nowadays, VCC is developing a new rear floor concept for the upcoming SPA3 platform, which will combine even more parts into the casting, reducing the number of parts in the rear floor significantly - combining 100 parts into one. For the industry to reach the high-set goals for sustainability and cost, it is of high importance that the product of large, single-die cast parts made out of recycled aluminum are robust to variations and disturbances in the production process.

The rear floor and its position in the car is illustrated below in Figure 1.1. This new rear floor will be manufactured using a large-scale variant of High Pressure Die Casting (HPDC), known within VCC as "mega-casting", which is the terminology that will be used in this thesis.

(a) Rear floor positioned in car, from [1]. **(b)** Mega-cast rear floor, adopted from [2].

Figure 1.1: Different views of the mega-cast rear floor.

HPDC is a process in which molten metal is injected into the die using a piston that accelerates the liquid metal to high speeds [3]. The die is filled within fractions of a second, reaching high pressures of up to 120 MPa [3]. In recent years large-scale HPDC, also known as mega-casting, has been gaining popularity in the automotive after it was introduced by Tesla [4]. Mega-castings reduce complexity in production by enabling multiple parts to be replaced by one single large die-cast part [5].

Such large-scale castings need to be integrated into the car body design and even though joining operations are reduced due to integration of parts, the remaining joints will be even more important. The quality of those joints are critical to fulfill requirements such as strength, crash-worthiness and aesthetics. In the following after-treatment steps, the part can undergo additional processing such as straightening, machining, and drilling in order to improve the geometrical quality. Another alternative to improve the geometrical quality is to optimize the geometry of the casting die to pre-compensate for distortion effects.

This master thesis is a part of a research project “geometrical robustness for mega-casted aluminum parts (GROMCAP)”.

1.2 Aim

The objectives of this master’s thesis is threefold. The first objective is to investigate and compare the geometrical quality between the different rear floor concepts. The second objective is to explore methods and processes aimed at improving the geometrical quality of the mega-cast rear floor concept. The third objective is to model and quantify the cost of geometrical quality of the mega-cast rear floor.

1.3 Scope

This project will cover the following areas:

- Investigate the geometrical quality by analyzing measurement data in the rear floors concepts (sheet metal floor, mixed sheet metal/cast floor, and mega-cast floor).
- Perform a literature study and conduct interviews with experts within casting, geometry assurance, manufacturing engineering, and other relevant fields to map methods and processing alternatives to improve geometrical quality of the mega-cast rear floor.
- Perform a literature study and conduct interviews with experts within geometry assurance and manufacturing engineering to model and quantify the cost of geometrical quality for the mega-cast rear floor concept.

1.4 Limitations

- The project will not include generating the data for the quantitative analysis of the geometrical quality and is therefore limited by the amount and quality of data provided by Volvo Cars.
- The project is limited by a time period of 20 weeks, therefore not all processes and methods to improve the geometrical quality will be investigated to the same extent.
- The cost of geometrical quality will exclude aspects that might induce cost after the product is produced, such as affect on goodwill, brand reputation or market share.
- The cost model will not include the entire manufacturing process of the car and will thus be limited the early stages in production, specifically the foundry and A-shop.

1.5 Research Questions

The research questions for the project are the following:

- How does the geometrical quality outcome differ between rear floor concepts (sheet metal floor, mixed sheet metal/cast floor, and mega-cast floor)?
- How and to what extent can the geometrical quality of the mega-cast rear floor be improved?
- How can the cost of geometrical quality be quantified and modeled for the mega-cast rear floor?

1.6 Specification of the Issue Being Investigated

Currently, there is no comparison of the geometrical quality of the different rear floor concepts. In order to accurately evaluate the rear floor concepts, the geometrical quality needs to be assessed. Additionally, methods and processes to improve the geometrical quality of the mega-cast rear floor need to be investigated and evaluated. Further, the relationship between geometrical quality and cost needs to be modeled in order to quantify the effect that geometrical quality has on cost. This is needed in order to evaluate manufacturing processes and guide strategic decisions.

1.7 Social, Environmental, and Ethical Considerations

From an ecological point of view, mega-cast production could cause high CO_2-emissions [5]. However, there are many potential positive aspects. Recycling of aluminum is of high importance to reduce the carbon footprint [5]. The casting process allows reuse of scrapped aluminum [6], implying that resource utilization can be much more efficient. This way, there is a potential to significantly reduce the level of scrap material. Further, by improving the geometrical quality of the mega-cast part, the overall quality of the cast component increases, which can reduce waste and scrap material. Also, reducing the required parts of the rear floor to one implies that much less parts have to be imported and transported. This reduces CO_2-emissions in relation to the supply chain.

Further, less suppliers in the supply chain might have a social impact as well since such suppliers lose a percentage of their customer base. Implementing mega-casting might reduce work for some employees since the production becomes further automated [5]. However, as with many innovations and new technologies, mega-casting might also create other jobs and opportunities. To exemplify, personnel from the body shop might be repositioned to the foundry [5].

When conducting the project, there will be some ethical considerations to account for. For example, interviews will be conducted which needs to be ethically carried out. For this matter, the interviewees will be properly informed about the topic, the purpose of the interview, and how the information gathered will be used. Further, the interviewees identities will be kept confidential if desired. All interviews will be performed with respect towards the respondents and in a suitable environment. Lastly, the selection of candidates will be done completely unbiased, as the focus is on gathering representative data.

2

Theory

This chapter presents the theoretical frameworks that are fundamental to understanding the main topics addressed in this thesis. The theory begins with an explanation of the relevant manufacturing methods: high pressure die casting and mega-casting. Additionally, key concepts and terminologies related to geometry assurance and cost modeling are introduced and discussed. Together, these theoretical frameworks provide the foundation necessary to support the information and findings in the subsequent chapters.

2.1 High Pressure Die Casting (HPDC)

High Pressure Die Casting (HPDC) is a process in which molten metal is injected into a metal mold at high speeds and solidifies under high pressure [7]. This is a manufacturing process that produces near-net shape parts [7]. HPDC is a suitable manufacturing method for high production rates and is applied in several industrial fields such as the automotive industry where approximately 60% of all light alloy castings are made by HPDC [3]. The main activities of the HPDC process can be seen in Figure 2.1.

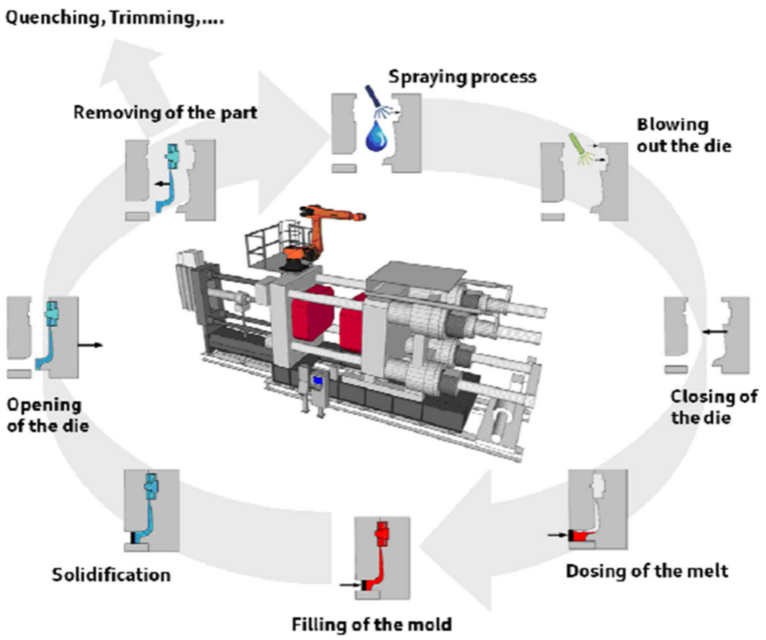


Figure 2.1: The process chain of HPDC, from [3].

High pressure die casting has in recent years increasingly been used to manufacture structural components within the automotive industry [8]. These structural parts often undergo after-treatment such as solutionization and aging to improve their mechanical properties [8].

HPDC is a complex process with a lot of process parameters which are difficult to keep constant, therefore defects are common [3]. These defects results in 5-10% scrap rate on average [3]. Parameters such as die temperature, mould filling capacity of molten metal, geometrical complexity and cooling rate significantly impact the integrity of the parts produced by HPCD [8]. Techniques like vacuum assistance during the HPDC process has been applied to reduce the defects and improve the mechanical properties [8].

2.2 Mega-casting

The term mega-casting is defined by [5] as "production of large high-pressure die-casting applications on high-pressure die-casting machines with a locking force of over 5000 kN". Mega-casting can therefore be seen as a large scale variant of HPDC. In the automotive industry a trend of utilizing structural castings can be identified [9]. Further, [5] presents a model for body in white (BIW) product concepts, which can be seen in Figure 2.2. It shows the product spectrum for BIW, ranging from a conventional multi-material mix welded concept (bottom left), to a fully mega-cast BIW (top right). Applying this model to Volvo Cars platforms, the SPA3 platform with a mega-cast rear floor can be classified as the 1+3-piece concept and the SPA1 platform as the muli-material mix concept, with the SPA2 somewhere in between.

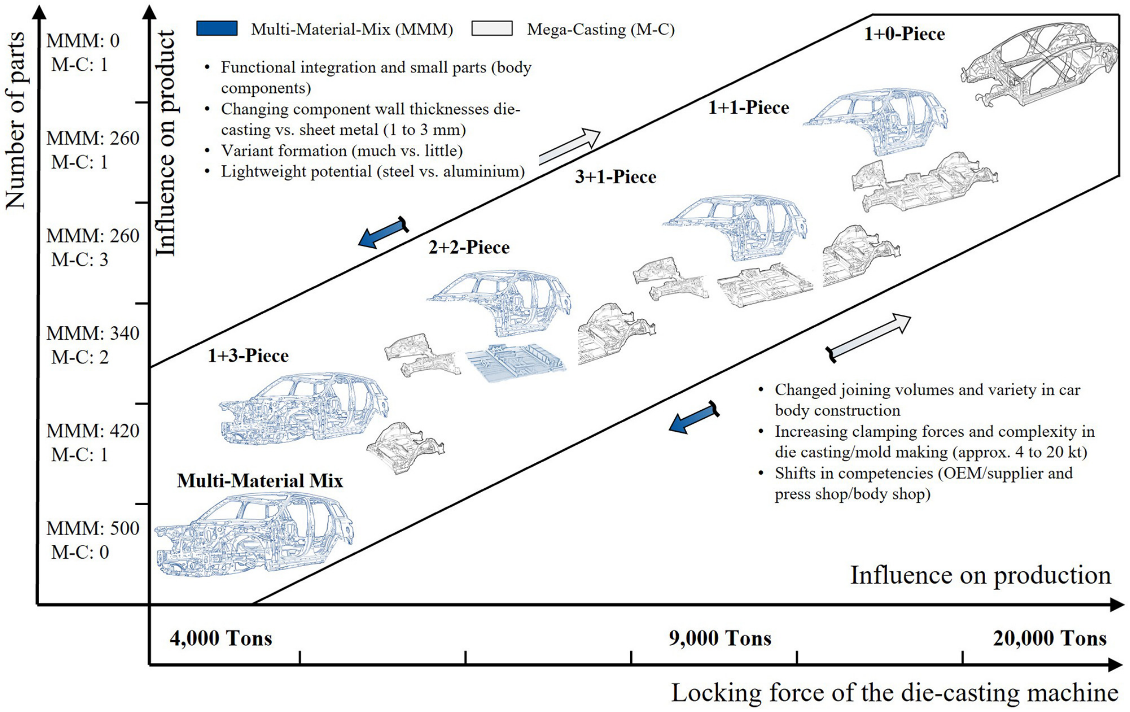


Figure 2.2: Number of parts versus locking force of the die-casting machine, from [5].

Currently, there is a development trend within the automotive industry to produce mega-casting body components [5]. For example, Tesla has applied mega-casting, referred to as Gigacasting at Tesla, in the manufacturing of the front and rear floor of the Model Y [5]. By doing so, a single casting replaced over 70 sheet metal parts and reduced assembly operations significantly [9]. However, although large-scale castings offer several significant advantages, [9] mentions some challenges and side effects with mega-casting. For example, there are only a limited amount of suppliers on the market producing the required tools, handling and transportation of a die weighing above 100 tons is challenging, and associated equipment, machinery and dies represent a huge investment. [9] also describes that casting large components in one shot entails that the design geometry of the part is not only determined by the loads it must support, but is also influenced by the requirements of the casting process itself. Thereby, a conflict between castability and structural strength arises which entails difficulties in achieving optimal weight. To clarify, lightweight design involves placing as little material as possible while optimizing structural integrity, which is contradicted by any single material component [9].

2.2.1 Mega-casting at Volvo Cars

In Figure 2.3, a simplified version of the mega-casting process used to produce rear floors at Volvo Cars is illustrated. This framework is constructed under supervision from, and with information provided by, Volvo Cars.

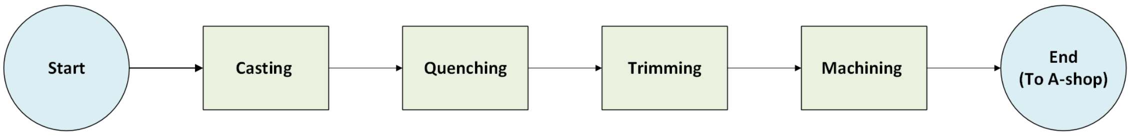


Figure 2.3: A simplified version of the mega-casting process at Volvo Cars.

In short, the casting process is built on the principles of HPDC, however the process is carried out at a much larger scale. In the casting process, molten metal is injected into a mold inside the die. The molten metal then solidifies rapidly under high pressure. Next, the part is taken out of the die and placed in a water tub to undergo quenching, which is a way to rapidly cool down the part. The part is then trimmed which entails removing any excess material such as the biscuit and runners. To clarify, when the part is taken out of the die, it consists of a lot of material that is not included in the final part. Such excess material includes overflows, the ingate, runners, and the biscuit, all of which serve a purpose connected to the casting process [10]. To exemplify, the runners and the ingate are required to direct molten material into the mold. Thus, the excess material serve a purpose which is necessary to be able to cast the part. However, it is not included in the final part and is therefore removed at a later stage. The part is then transported to the machining where additional processing on the part is done, such as milling to ensure accurate mating surfaces, and drilling holes required for later assembly operations. The part is then transported from the foundry to A-shop (also known as body shop), to proceed with assembly together with other necessary parts to complete the car body.

2.3 Geometry Assurance

The purpose of geometry assurance is to reduce the impact of geometrical variation, which applies on both part and assembly level [11]. There are many sources of variation in a product such as the part manufacturing process, material, the joining process, etc., and it is important that this variation is managed in order to achieve the product requirements [11]. Another term related to geometry assurance, which is also closely connected to geometrical variation, is geometrical deviation. Geometrical variation can be measured by the variation of the geometrical deviation for different parts manufactured by the same process [11]. Geometrical deviation can be defined as "the deviation from the nominal shape for one part or the mean-value deviation from the nominal shape for a set of parts" [11], where the "nominal" refers to what is perfect in theory.

Geometry assurance consists of several activities that span throughout different phases of the product realization process, all of which help to minimize geometrical variation for the end product [12]. To exemplify, in the production phase, the focus of geometry assurance is to examine collected data points (representing the geometry) to control production by detecting and correcting errors [12]. In relation to geometry assurance activities, there are several tools that can be utilized. Examples are locating scheme optimization and variation simulation, both of which can be done within a Computer Aided Tolerancing-software (CAT) such as RD&T [12].

2.3.1 Geometry Assurance in Mega-casting

In [11], several challenges related to geometrical quality of mega-castings are presented. The challenges span from early in the product development phase through pre-production and full production, focusing on geometry assurance of parts involving mega-casting. In total, nine challenges (C1 - C9) are presented and divided into two separate domains (either physical or simulation) and two different levels of priority (either first or second). Some of these challenges are outlined here, as they are relevant in relation to the topic of this thesis. C1 and C2 are both within the physical domain and of highest priority. For C1, the task is to quantify the expected variation, both for process parameters such as die temperature and pressure and the material parameters, related to the mega-casting process. After solving C1, C2 can be addressed. This challenge is to gather knowledge about the expected distribution of geometrical deviations resulting from the mega-casting process. Further, C5 is also in the physical domain, with second priority, and involves assessing the possible effects of residual stresses occurring during the mega-casting process. C6 and C7 are both within the simulation domain, with second priority, and focus on predicting part deviation through simulation (C6) and developing a method with the use of CAT tools to utilize the results from the simulation as inputs to the method.

2.3.2 Tolerance Limits & Geometrical Quality

Tolerance limits, also known as specification limits, are the upper and lower specifications (in short USL & LSL) which together outlines the acceptable range of values for which a product should operate within [13], [14]. This is shown below in Figure 2.4.

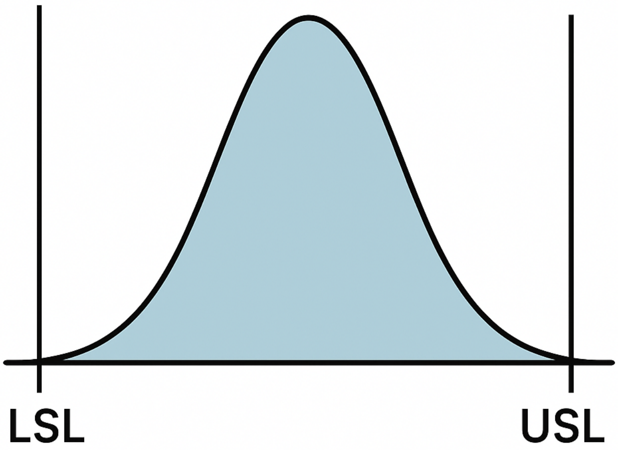


Figure 2.4: Specification limits (tolerance limits).

The tolerance limits are illustrated within a product control chart where two parallel lines are drawn (which illustrates the acceptable range) in relation to time [14]. Because specification limits (or tolerance limits) depicts the targeted performance of a process, such limits enables the ability to assess the process capability of fulfilling requirements [13]. Further, it should be noted that specification limits (or tolerance limits) differ from control limits. Control limits are calculated with respect to collected data and therefore demonstrates the actual performance of the process, which allows assessment of process capability [13].

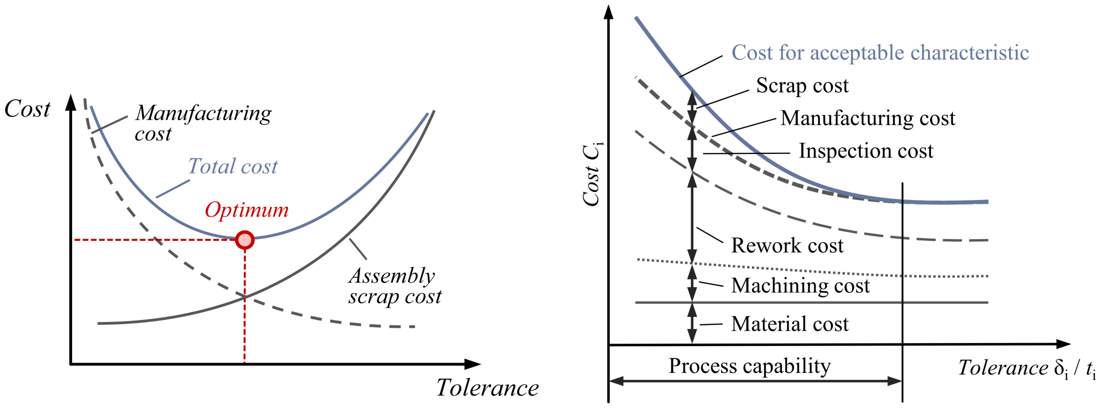
In [15], many different views and definitions of quality with the support of many prior studies are outlined. One of these definitions are presented as "conformance to specifications", where specifications refers to the tolerances (or target specifications) that are determined by the designers. Further, a more subjective side of quality is presented is presented where other definitions are targeted towards fulfilling the needs of the customers. However, when it comes to geometrical quality, there seems to be no commonly used definition, although the term itself is widely used in literature. Therefore, in this thesis, geometrical quality will refer to the conformance to specification which in this case implies the tolerance limits defined for a certain measurement point. To exemplify, "good" quality here would be measurement points being within the tolerance limits, whereas "poor" quality would be measurement points falling outside tolerance limits.

2.4 Cost & Quality

In this section, concepts and theory related to cost and quality is presented. Additionally, closely related concepts and terminology such as tolerances are presented in relation to cost and quality.

2.4.1 Tolerance Cost Optimization

In [16], the concept of tolerance allocation is outlined with the support of many prior studies. It is explained in [16] that that tolerances are generally allocated to ensure functionality and is often grounded in expertise or empirical data. Thereby, tighter tolerances are typically assigned to prioritize product quality which raises manufacturing costs but keeps product quality at a high level. Ultimately, this presents a challenge for manufacturers in creating balance between quality and cost when allocating tolerances. This challenge is presented below in Figure 2.5a. In [16], the impact of tighter tolerances in relation to manufacturing costs, can be further assessed in a tolerance-cost function, presented below in Figure 2.5b.



(a) Quality-cost conflict, from [16]. **(b)** Tolerance-cost function, from [16].

Figure 2.5: Cost in relation to tolerances.

Some variables from Figure 2.5b are fixed and thus have a constant value, for example the material cost, since such costs are independent of the tolerance level. Other costs are variable costs and dependent on the tightness of the tolerances. In [16], it is explained that tighter tolerances require more precise tooling, extra manufacturing operations, tuning of process parameters, etc. In [16], it is also explained that tighter tolerances put higher requirements on inspection to measure the part, increasing inspection costs. Further, higher precision in tolerances increases both the number of parts requiring rework and the amount of scrap, thereby raising costs for both scrap and rework.

2.4.1.1 Taguchi's Quality Loss Function

In [16], the concept of quality loss based on the idea of Taguchi is described. The principle of Taguchi's idea is that any deviation from the optimum target value is perceived by the customer as a loss of quality. Thus, in order to improve product quality, a customer-centric approach must be incorporated to achieve optimal tolerance allocation. This is different from a traditional approach towards quality loss, where the assumption is that any deviation within the specification limit, does not impact the customers' perception of quality [16]. An illustration of the traditional view versus Taguchi's approach is illustrated below in Figure 2.6.

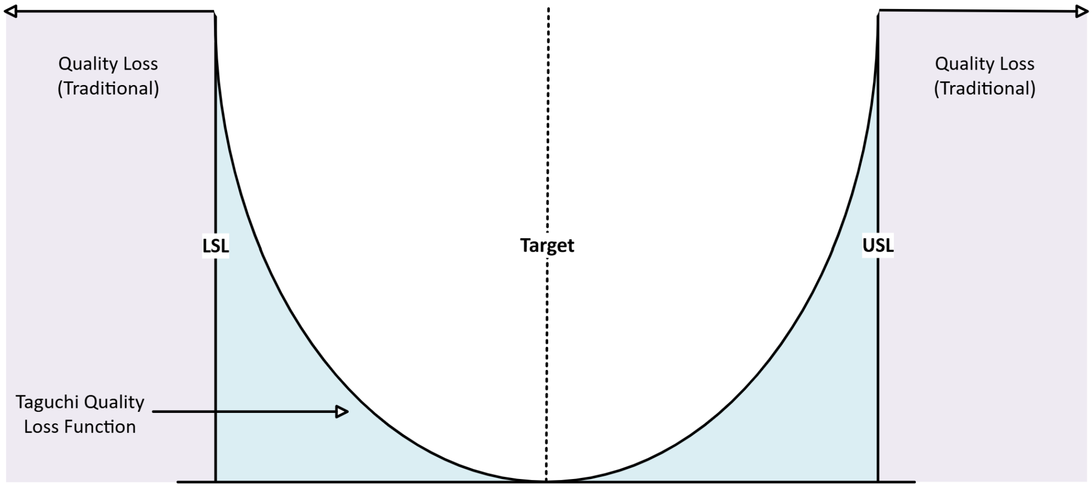


Figure 2.6: Taguchi quality loss function vs. traditional approach, adopted from [16].

2.4.2 Net Present Value

Net Present Value (NPV) represents the present value of all future expected cash flows, discounted at the required rate of return and compared to the initial investment [17]. In short, NPV is a way to evaluate the expected return of an investment and can thereby serve as a guide when deciding whether to invest in a project [17]. NPV is calculated according to Formula 2.1 presented below (adopted from [17]).

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} - I_0 \tag{2.1}$$

Where:

- t - The time period (yearly).
- C_t - Cash flow at year t.
- r - The discount rate.
- I_0 - Initial investment.

3

Geometrical Quality Outcome of Rear Floor Concepts

In this chapter, the geometrical quality outcome will be analyzed for the rear floor concepts: sheet metal floor (SPA1), mixed sheet metal/cast floor (SPA2), and fully cast floor (SPA3). This will be done through data analysis of the geometrical deviation. The selection of measurement points and statistical methods are explained in Section 3.1. The results of the data analysis are presented and discussed in Section 3.2 and Section 3.3, respectively.

3.1 Methodology

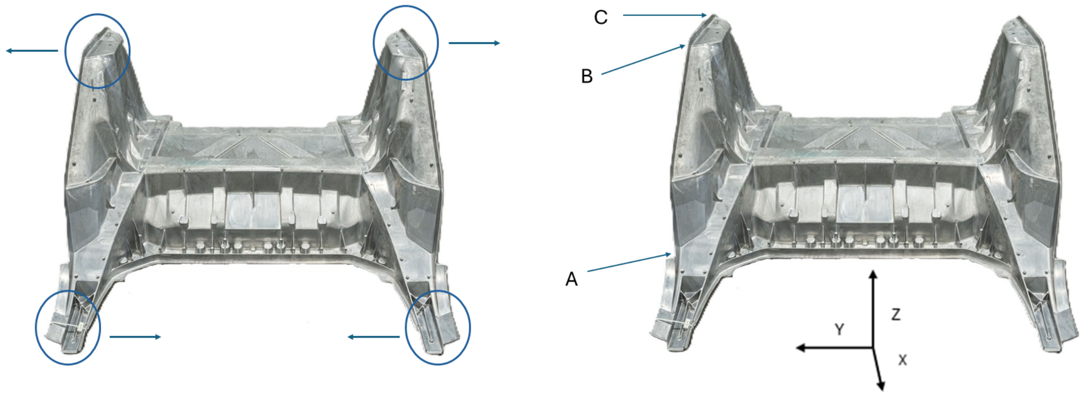
This section outlines the methodology employed in this study to assess the geometrical quality outcomes of rear floor concepts across multiple platforms. It outlines the methodology of two major parts, the selection of the measurement points and the statistical analysis.

3.1.1 Selection of Measurement Points

In order to assess the geometrical quality of the rear floor concepts, relevant measurement points had to be selected first so that a comparison can be made between the rear floor concepts. The relevancy of the points refers to those points that enable the most valid comparison between the platforms, which requires several considerations to account for. One consideration is to select the points that are mostly affected (distorted) by the mega-casting process and critical for the subsequent joining processes. These points lie within the areas of the SPA3 platform that exhibits particularly high geometrical deviation, which was established by [10] and can be seen in Figure 3.1a. Therefore, these areas serve as a reference for selection. Thus, when choosing the points, a point for SPA3 is selected at first, and then points are selected for SPA1 and SPA2. Another consideration when selecting the measurement points is that the points have to be selected with similar coordinates for the different platforms. To clarify, one measurement point has three coordinates in x-, y-, and z-direction. In order to select appropriate measurement points for comparison, these coordinates had to be similar for the different measurement points connected to each platform. As an example, if a point on the front legs for SPA3 is selected, a point with similar coordinates is chosen for both SPA2 and SPA1 to ensure that the comparison is made roughly at the same location. Because the floors do not have identical designs, selecting points with the exact same coordinates is not possible. Another consideration is that all measurements must be in the same direction, i.e. the geometrical deviation is measured as how much a point varies from its nominal position in the y-direction. This is illustrated in Figure 3.1b. In this project, the selection of measurement points was carried out in collaboration and supervision from Volvo Cars. The three following measurement points were selected within the two identified critical areas (see Figure 3.1b).

- Measurement point A (MPA) - Located on the front legs.
- Measurement point B (MPB) - Located on the on the front of the wheelhouse.
- Measurement point C (MPC) - Located on the back of the wheelhouse.

For the data analysis, this meant that three measurement points for each platform is used as an input (resulting in nine points in total) where each point contains a dataset that shows the geometrical deviation of a certain time period. This will be illustrated in Section 3.2. All points were retrieved from Volvo Cars database using the software CM4D.



(a) Identified critical areas by [10] and direction of distortion (adopted from [2]).

(b) Selected measurement points for data analysis (adopted from [2]).

Figure 3.1: Mega-cast rear floor.

In Figure 3.1b, it should be noted that measurement points were only selected for the right side of the rear floor due to several reasons. Firstly, the geometrical deviation of the right side of the rear floor is generally worse. This is because the left side is used as a reference point where the geometry spans out over the y-axis to the right side. Therefore, more variation is likely to occur on the right side of the rear floor and thus it is more representative to select a sample of measurement points from this side for assessing the geometrical quality. Secondly, the geometry of SPA1 is not symmetric, which means that the wheelhouses look different on each side. This meant that no point with similar coordinates could be found on the left side that corresponds to the point on the right side. Therefore, a direct comparison from the left and right side was not possible. Since the geometry was more consistent among the platforms for the right side, this side was selected to ensure that a valid comparison could be made.

3.1.2 Data Analysis

The purpose of the data analysis is to analyze the geometrical quality outcome of the SPA3 platform in comparison to SPA1 and SPA2. In Figure 3.2, the overall process of the data analysis is visualized. The most relevant aspects for the geometrical quality is the variance and the mean of the geometrical deviation, i.e. the spread and average geometrical deviation. The first step of the data analysis is aimed to get initial insights about the variance and mean of the datasets. Therefore, graphical methods, time-series and box-plots are applied first. In order to determine what subsequent methods to deploy, explained in more detail below, the data sets have to be tested for normality. To gain further insights about the variance and mean of the datasets in relation to the specification limits, process performances are calculated and visualized with histograms. The last part of the data analysis is to establish if there is a statistical significant difference of the mean and variance between the datasets. Statistical analysis software can be used to analyze the data. In this project, Minitab was exemplarily used.

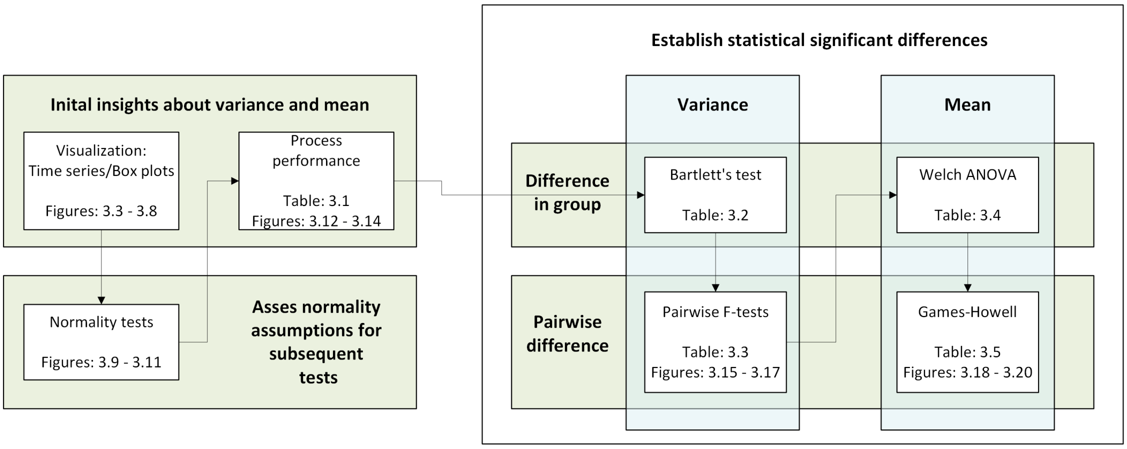


Figure 3.2: Flowchart of the data analysis process.

The datasets of the measurement points (MPA, MPB, and MPC) for the three platforms (SPA1, SPA2, and SPA3) are all visualized to get a first understanding about the data. In order to evaluate the quality of the datasets, time-series are set up for each of the platforms with belonging datasets for each measurement point. The purpose of this is to discover abnormal patterns and trends in the data. This way, if a deviating pattern was discovered, this could then be further investigated and discussed with Volvo Cars in order to make a decision whether to filter out and exclude certain patterns of the data, or not. To exemplify, some patterns of the data could be explained by assignable causes and thus did not arise due to natural variation. It is deemed necessary to exclude such patterns since keeping it could lead to misleading and unreliable results. Thus, boxplots can be used to visualize and compare the ranges of the datasets for the different platforms at each measurement point.

Assessing if the datasets can be assumed to follow a normal distribution is crucial in deciding what methods to use for the subsequent tests. There are a wide variety of methods that can be used to test a dataset for normality, among the most common are Shapiro-Wilk, Kolmogorov-Smirnov, and Anderson-Darling [18]. Further, literature suggests that Shapiro-Wilk's test has the most statistical power for a variety of distributions [19], [20]. However, literature also suggests that the Anderson-Darling test is comparable with Shapiro-Wilk's test [19]. Due to availability in the statistical software used, the Anderson-Darling test was used to asses if the data was normally distributed.

In order to evaluate how well the datasets are able to deliver values within the specification limits, i.e. how many of the geometrical deviations that are within tolerance limits, a normal capability analysis can be conducted. According to [21], a requirement for performing such an analysis is that the data must follow a normal distribution, otherwise the process capability can be calculated using other distributions. When performing a capability analysis, there are generally two categories to account for: overall capability and potential capability. The overall capability accounts for the overall variation of the process, thereby including differences between subgroups, while the potential capability only accounts for variation within sub-groups, thereby excluding the variation between them [22]. Thus, the overall capability is a measure of actual performance, while the potential capability is a measure of how the process could potentially perform if variation between subgroups was excluded [22]. The data analysis focuses on comparing the current state of the platforms and it is therefore of interest to determine the actual performance. Considering this and the results of the Anderson-Darling test, a normal capability analysis was conducted for the overall capability measurements: Pp and Ppk. If the data is not normally distributed other distributions can be used to calculate the Pp and Ppk [21]. Pp measures the overall capability of the process and is based on the overall standard deviation of the process [23]. Ppk is another measurement of overall capability of the process, however it also accounts for the location of the variation of the process in relation to the specification limits [23]. Pp and Ppk was calculated for each of the datasets.

There are multiple tests that can be used to establish if the variance of two or more datasets statistically significantly differ from each other [24]. In [24], recommendations are given for what test to use in different situations. For multiple samples that are normally distributed and have small sample sizes, Bartlett's test and Cochran's test are recommended [24]. If the data is not normally distributed, Levene's test is recommended for multiple samples. Considering the results of the Anderson-Darling test and the available methods in the statistical software used, the Bartlett test was selected. Bartlett's test was used to determine if there was a statistically significant difference between any of the datasets for each of the measurement points. Additionally, to identify between which datasets, if any, there is a statistically significant differences, pairwise comparisons were conducted. For comparing the variance of two datasets F-test or Bartlett's test is recommended for small sample sizes of normally distributed data [24]. If the data is not normally distributed Levene's test is recommended [24]. Due to availability in the statistical software F-tests were performed comparing each dataset with the other two for all the platforms.

Lastly, to asses if there is a statistically significant difference between the means of the datasets, an analysis of variance (ANOVA) can be carried out. In order to perform such an analysis, there are some assumptions that need to be met. The data has to be normally distributed and the variances in each group must be similar [25]. If these assumptions are not met, there are other methods that can be performed. If the data is non-normal, a Kruskal-Wallis test can be utilized instead, and if the data is inhomogeneous, a Welch-ANOVA can be conducted [25]. The datasets were tested for normality with the Anderson-Darling tests, and tested for homogeneity by utilizing Bartlett's test. These results dictated that a Welch-Anova had to be carried out. The Welch-ANOVA was performed in order to evaluate if there was a statistical significant difference across the datasets by comparing the means of the respective groups with each other. Welch's ANOVA only shows if there is a statistical significant difference in the means across the datasets, it does not specify which datasets differ from each other. In order to determine where the differences lie, a pairwise comparison of the means of each of the datasets can carried out after the ANOVA. According to [26], what type of pairwise comparison that can be made depends on if equal variances among the datasets can be assumed or not. If equal variances can be assumed, there are many methods to choose from such as Tukey or Fisher. However, if equal variance cannot be assumed, the Games-Howell method can be applied. Because the datasets had proven unequal variances from Bartlett's tests, equal variances could not be assumed for the pairwise comparison which meant that the Games-Howell method had to be used. The pairwise comparison was also visualized with confidence intervals of the mean value for all the platforms at each measurement point.

3.2 Results

This section presents the visualization and analysis of data from three platforms (SPA1, SPA2, and SPA3) across three measurement points (MPA, MPB, MPC). The results are structured into five major parts corresponding to the methodology.

3.2.1 Visualization of Data

The datasets for MPA, MPB, and MPC, were visualized in time series for SPA1, SPA2, and SPA3 separately and can be seen in Figures 3.3, 3.4, and 3.5. The time series show the geometrical deviation over time from the nominal in comparison to upper- and lower specification limits (USL and LSL). The sample sizes used for the datasets are listed below:

- SPA1 - 479 samples for all measurement points.
- SPA2 - 25 samples for MPA and MPB, 24 samples for MPC.
- SPA3 - 15 samples for all measurement points.

For SPA1, shown in Figure 3.3, it can be noted that MPB has a few samples that are outside the USL in the beginning of the series, while the samples of MPA and MPC are within the limits. For SPA2, shown in Figure 3.4, one sample of MPB is outside the USL, while several samples of MPC are outside the LSL. On the other hand, all samples of MPA remain within specification limits. For SPA3, shown in Figure 3.5, one sample of both MPA and MPC are outside the LSL.

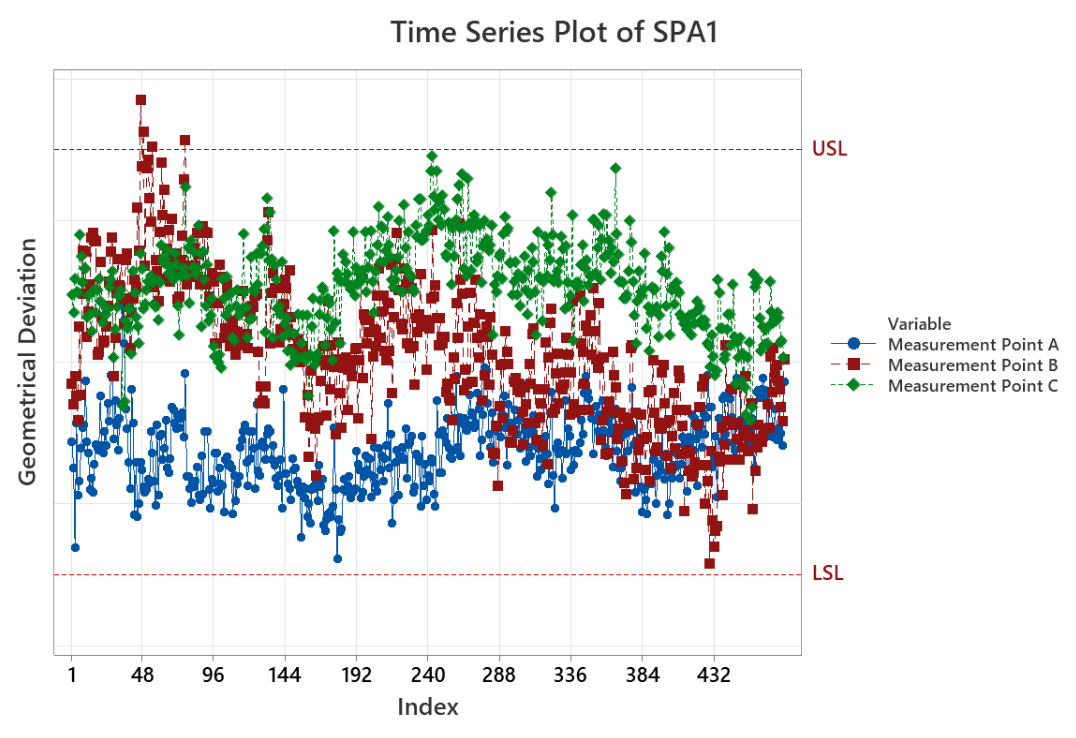


Figure 3.3: Time series of SPA1.

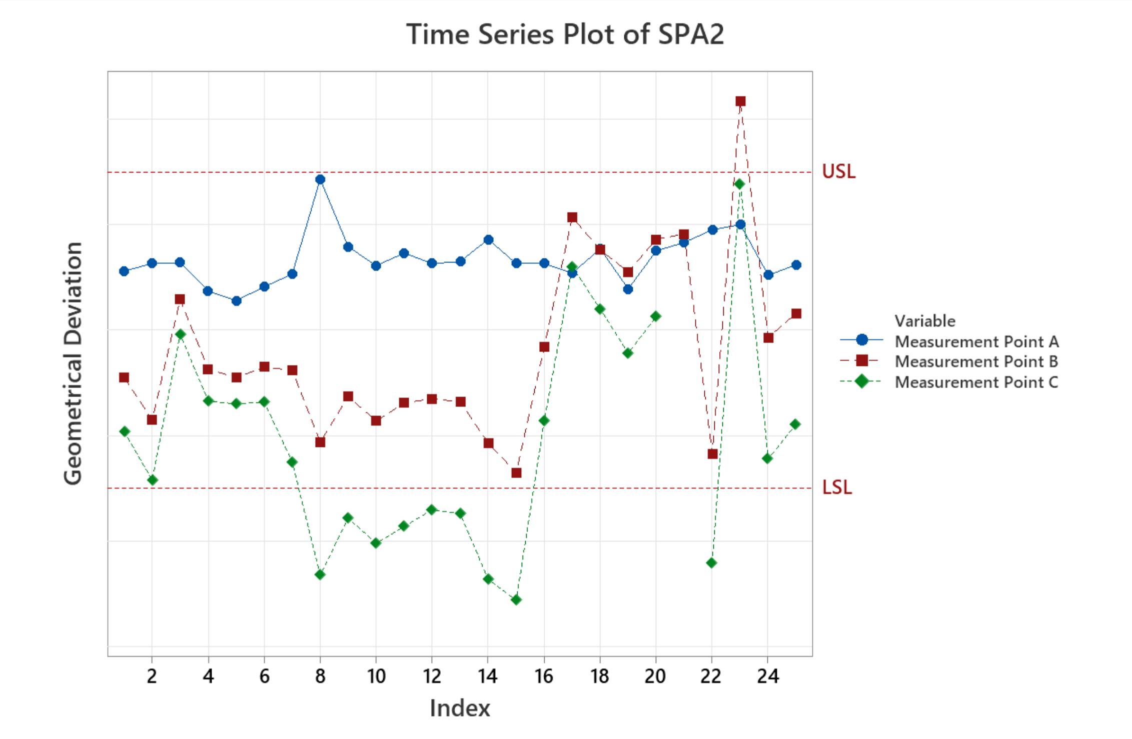


Figure 3.4: Time series of SPA2.

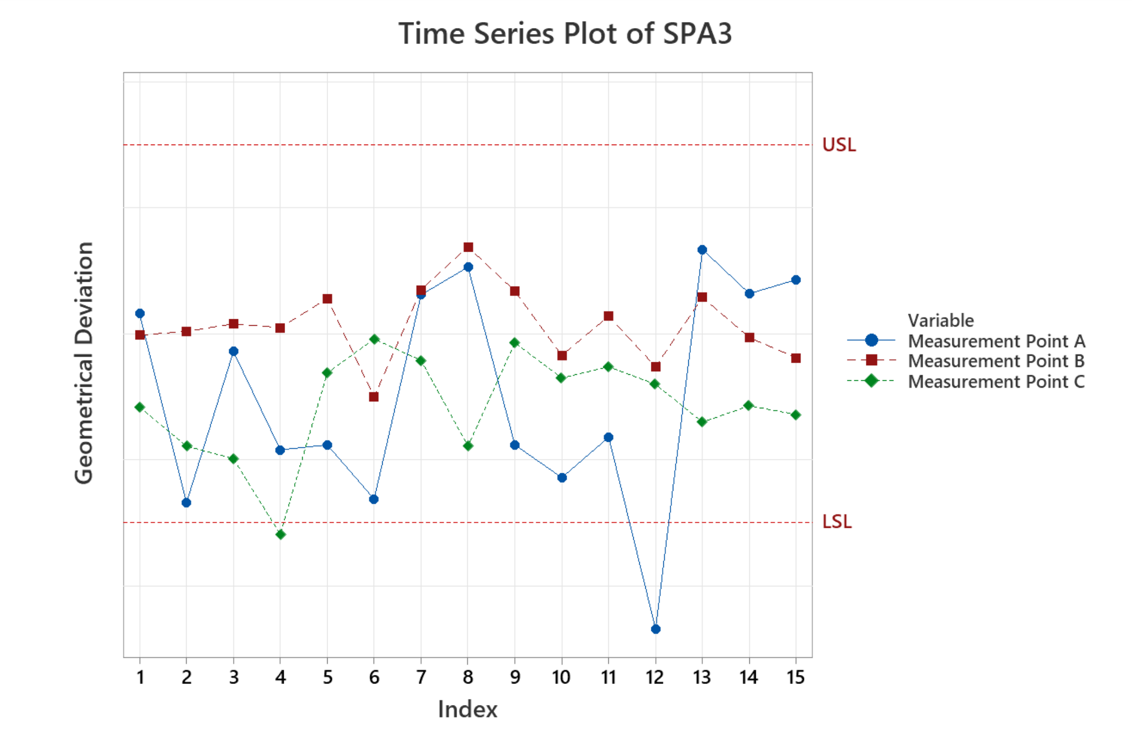


Figure 3.5: Times series of SPA3.

The datasets of all platforms for each of the measurement points MPA, MPB, and

MPC are further visualized in separate boxplots, where each boxplot illustrates the same measurement point across all platforms. To exemplify, Figure 3.6 shows the boxplots of MPA for SPA1, SPA2, and SPA3. The remaining boxplots are presented in Figures 3.7 and 3.8. For MPA, shown in Figure 3.6, it is noted that SPA3 has both a higher interquartile range (IQR) than SPA1 and SPA2, indicating a greater spread in the data. It is also noted that the median of SPA3 is located further down toward the first quartile (Q1), indicating a skewness in the dataset. In the same Figure, it is also observed that the datasets of SPA1 and SPA2 are located in different positions in relation to the specification limits, with SPA1 closer to the LSL and SPA2 closer to the USL.

For MPB, shown in Figure 3.7, it is noted that SPA2 shows the highest IQR among the platforms, indicating a greater spread in the data compared to SPA1 and SPA3. The median of SPA2 is also closer to Q1, indicating a skewness in the dataset. Further, both SPA1 and SPA2 show higher ranges than SPA3. Another observation is that the dataset of all three platforms seems to be centered in about the same location relative to the upper and lower specification limits.

For MPC, shown in Figure 3.8, it is observed that SPA2 shows the highest IQR, indicating a greater spread in the dataset compared to SPA1 and SPA3. Furthermore, the IQR of SPA2 shifts toward the LSL so much that Q1 reaches beyond the LSL. Another observation is that SPA2 and SPA3 have their IQRs close to the LSL, while SPA3's IQR is spread closer to the USL.

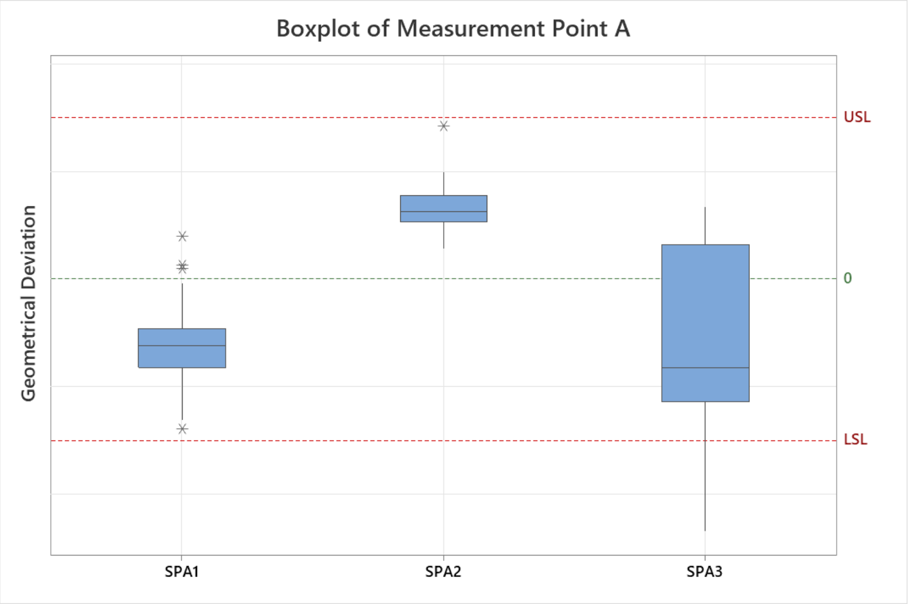


Figure 3.6: Boxplot of MPA.

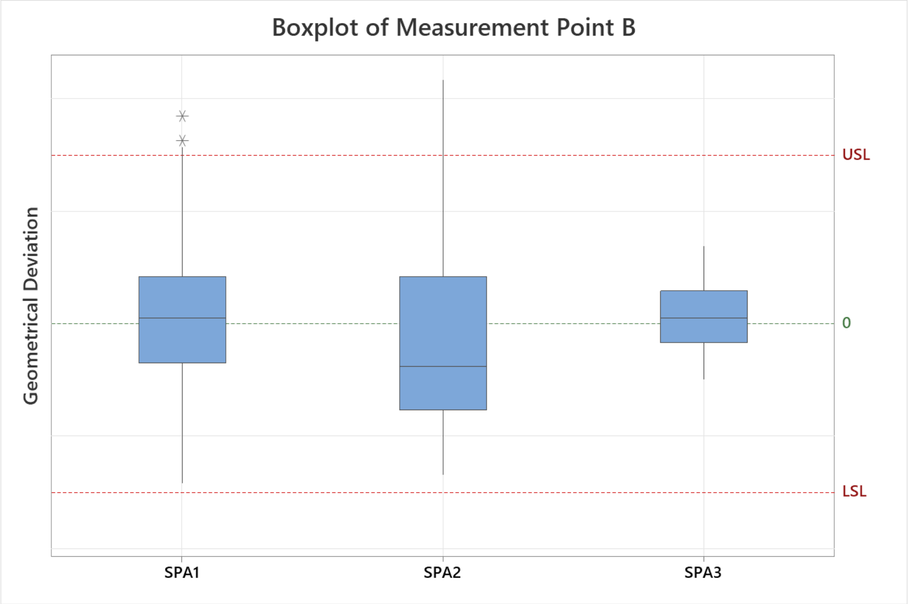


Figure 3.7: Boxplot of MPB.

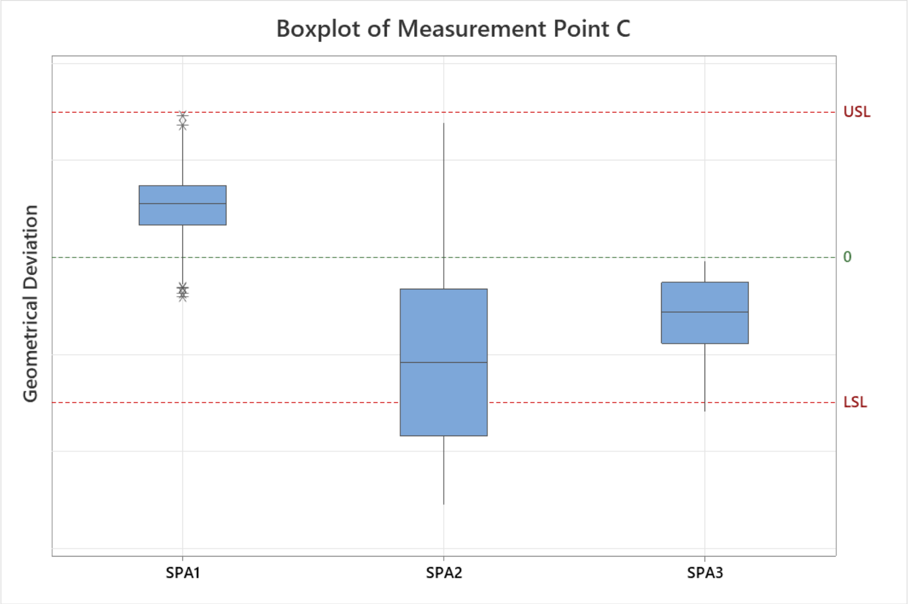


Figure 3.8: Boxplot of MPC.

3.2.2 Normality Test

The normality tests are performed using Anderson-Darling tests on all the datasets. The results can be seen in Figures 3.9, 3.10, and 3.11. For the testing, a significance level (alpha) of 0.05 is used. The null hypothesis is that the data follow a normal distribution, and the alternative hypothesis is that the data do not follow a normal distribution. Since the P-values of all the separate normality tests are over 0.05, the null hypothesis cannot be rejected for any of the tests. Hence, with

95% confidence, it cannot be ruled out that all datasets follow a normal distribution. Therefore, for the following statistical methods, all datasets are assumed to be normally distributed.

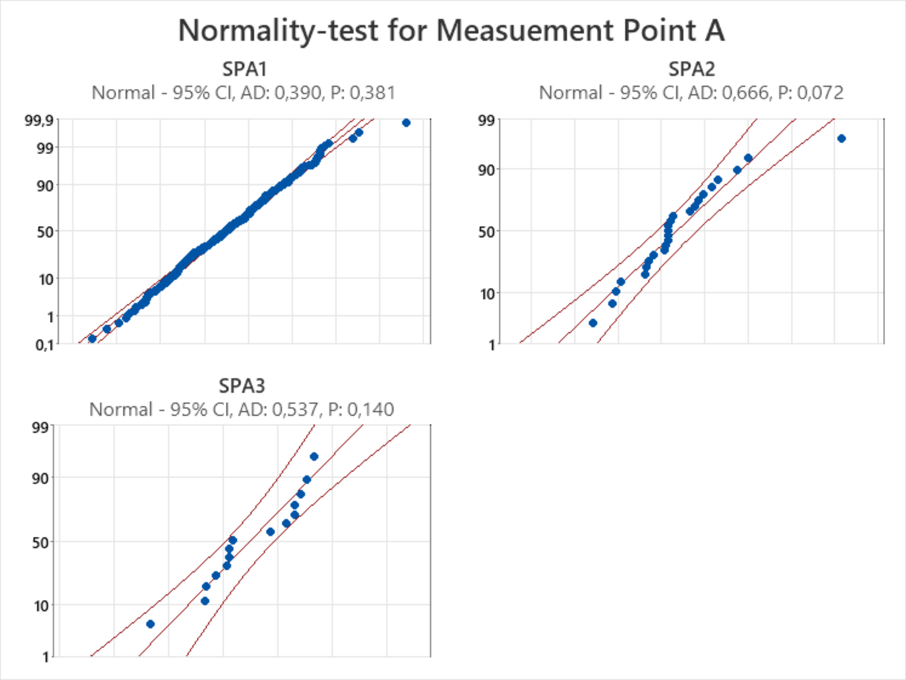


Figure 3.9: Normality test MPA.

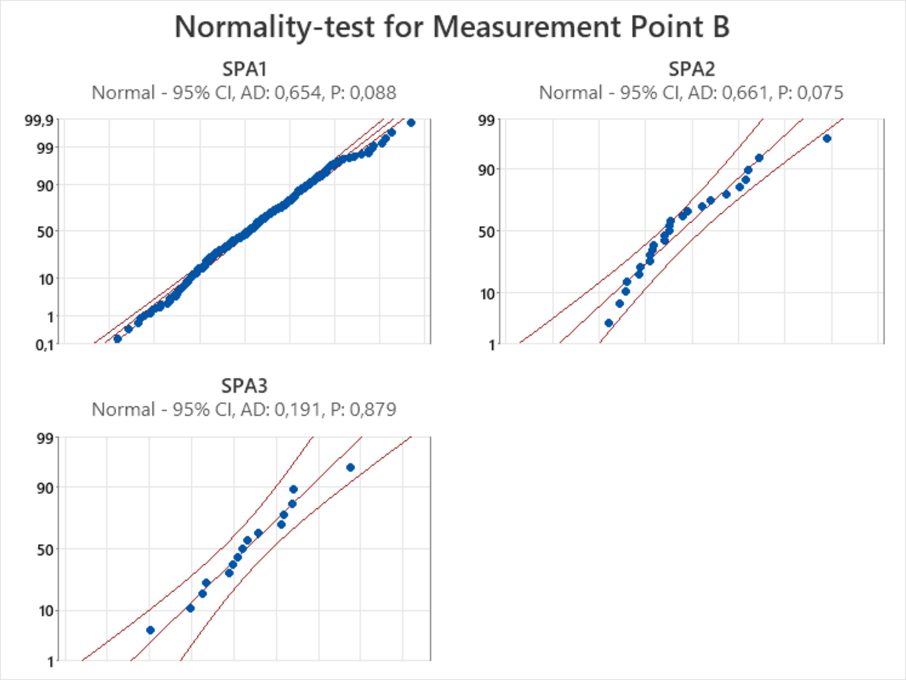


Figure 3.10: Normality test of MPB.

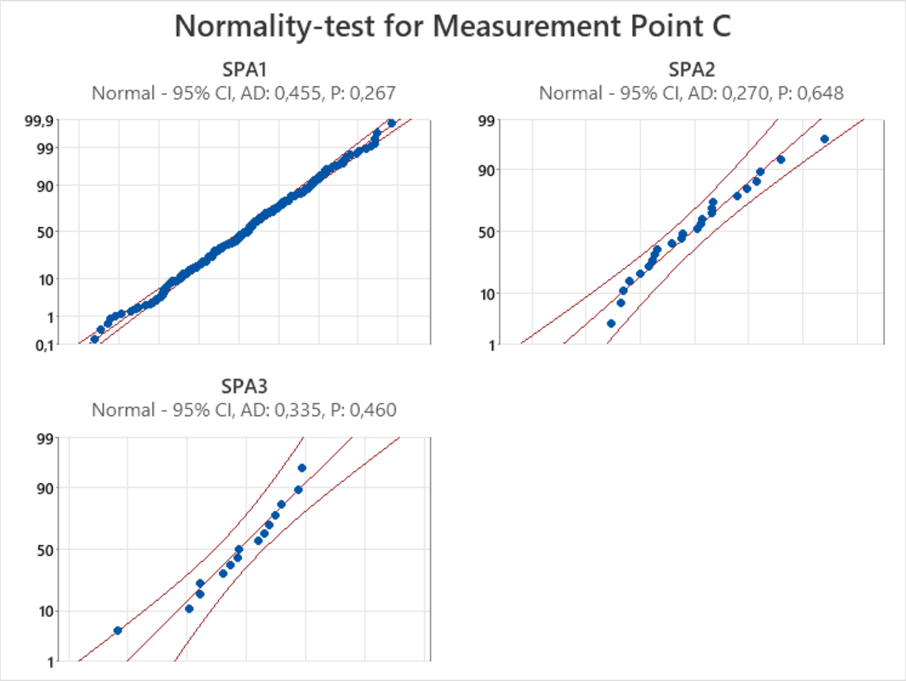


Figure 3.11: Normality test of MPC.

3.2.3 Process Performance

The process performance, where the process is defined as the total of the activities conducted before the measurement is taken, is assessed across the platforms. For each measurement point, the geometrical deviation of all platforms is evaluated in relation to the specification limits. In Figures 3.12, 3.13, and 3.14, a histogram of the collected data is shown in relation to the specification limits. Further, the process performance is evaluated with both Pp (not considering shift) and Ppk (considering shift), where the process spread (six standard deviations) is compared with the specification limits. The results of this can be seen in Table 3.1.

	Dataset	**Pp**	**Ppk**
MPA	SPA1	1.959	1.141
	SPA2	2.121	1.174
	SPA3	0.566	0.381
MPB	SPA1	0.959	0.928
	SPA2	0.592	0.521
	SPA3	1.700	1.618
MPC	SPA1	1.585	1.017
	SPA2	0.489	0.148
	SPA3	1.222	0.761

Table 3.1: Summary of process capability.

For MPA, the results indicate that the datasets for SPA1 and SPA2 have lower variation than the dataset of SPA3. This can be seen in Figure 3.12, where the spread is much larger in comparison to the specification limits. The dataset of SPA3 has a Pp of 0.566 and Ppk of 0.381, indicating that the process has a lot of variance compared to the specification limits and that the process is not centered since the Ppk is significantly lower than Pp. SPA1 and SPA2 have a Pp of 1.959 and 2.121, which imply that the range of the specification limits is around twice as wide as six standard deviations for the process. This indicates that very few of the parts produced fall outside of the specification limits assuming that the process is centered. However, the Ppk values for SPA1 and SPA2 are 1.141 and 1.174, respectively, indicating that both processes are not centered since the Ppk value is significantly lower than the Pp value.

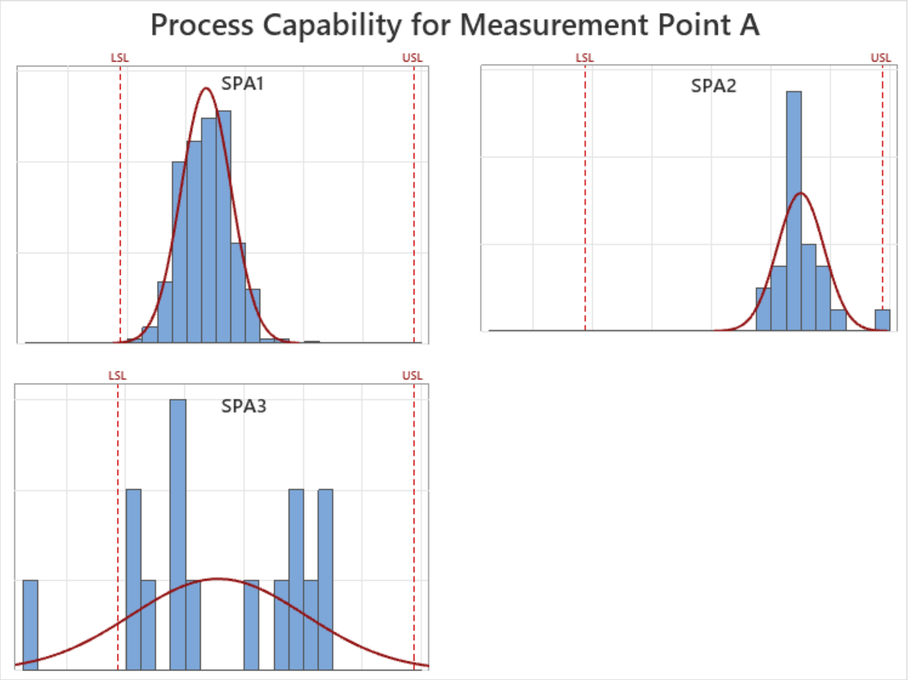


Figure 3.12: Process capability of MPA.

For MPB, the dataset of SPA3 performed significantly better than in MPA. It had a Pp of 1.700 and a Ppk of 1.618, signaling that the variance of the process is small compared to the specifications limit and that the process is relatively centered since the Ppk is close to Pp. The dataset for SPA2 indicates that the process has a lot of variance in relation to the specification limits, with a Pp of 0.592. However, the process appears to be relatively centered with a Ppk of 0.521 which is similar to the Pp value. The dataset for SPA1 had a Pp of 0.959 and Ppk of 0.928 which indicates that the process is centered and that six standard deviations are somewhat similar to the range of the specification limits. This would result in about 0.27% of the produced parts to fall outside of the specification limits, assuming a stable process.

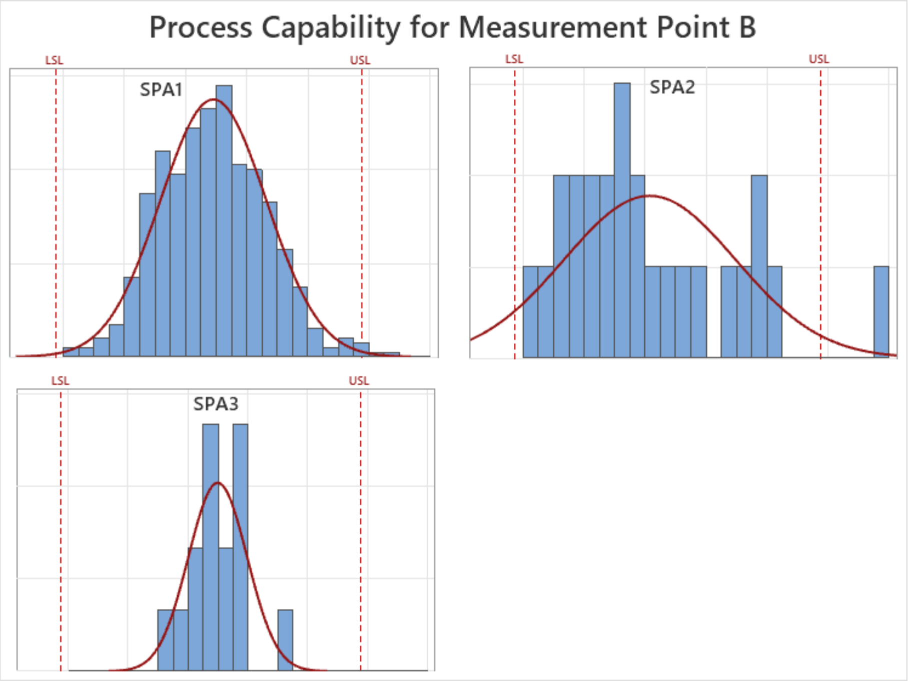


Figure 3.13: Process Capability of MPB.

For MPC, the datasets for SPA1 and SPA3 have Pp values of 1.585 and 1.222, respectively, indicating that six standard deviations of the processes fall within the range of the specification limits. However, the Ppk is significantly lower than the Pp: 1.012 for SPA1 and 0.761 for SPA3, indicating that the processes are not centered. The dataset of SPA2 performs worse and has a Pp of 0.489 and a Ppk of 0.148, which indicates that the variance of the process is large compared to the specification limits and that the process is not centered.

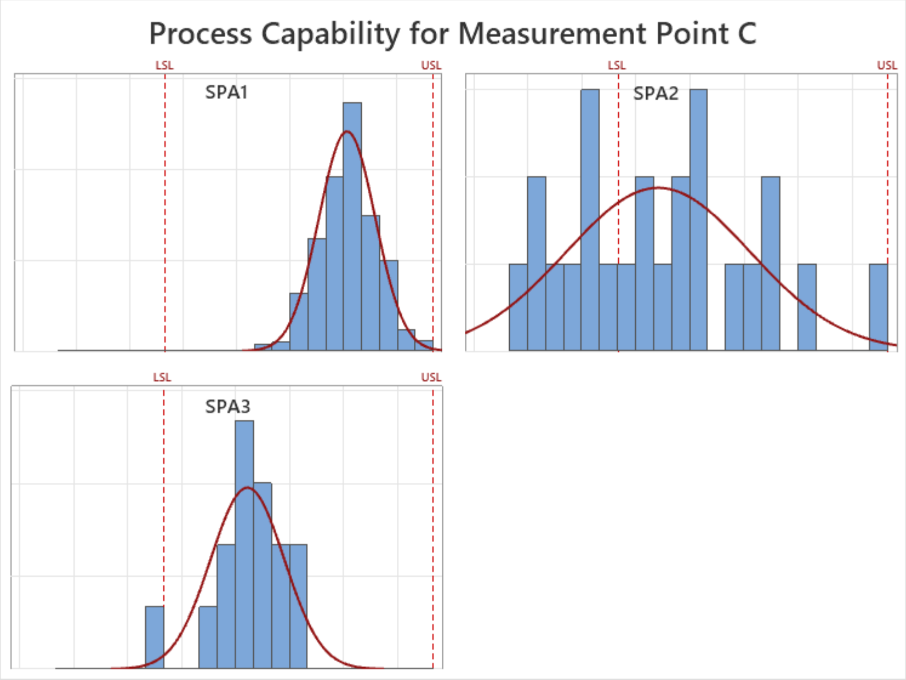


Figure 3.14: Process Capability of MPC.

3.2.4 Variance

The variance of the geometrical deviation in the different platforms is analyzed for each of the measurement points using the Bartlett test. Therefore, all datasets for each measurement point are tested to determine if a statistically significant difference between the variances can be established. The results of this can be seen in Table 3.2. The null hypothesis for this test is that the variances of all datasets for each of the measurement points are equal, and the alternative hypothesis is that the variance of at least one of the datasets differs from the others. Since the P-values for all of the tests are less than the significance level of 0.05, the null hypothesis is rejected, and a statistically significant difference between the variances of the datasets can be established.

Measurement point	Test statistic	P-value
A	98.83	0.000
B	21.14	0.000
C	124.81	0.000

Table 3.2: Results of Bartlett tests for each of the measurement points.

Further, pairwise F-test are carried out to establish between which of the datasets for each of the measurement points the variance differs. The result of this can be seen in Table 3.3. For these tests, the null hypothesis is that the variances are equal and the alternative hypothesis is that the variances differ from each other. For MPA, the variance of the dataset of SPA3 can be established to significantly differ from the other two since the P-values are below the significance level of 0.05. A statistically significant difference in the variance between the datasets of SPA1 and SPA2 cannot be established since the P-value is above the significance level of 0.05. For MPB, the variance can be established to differ between all the datasets since the P-value of all the tests is below the significance level of 0.05. For MPC, the variance of the dataset of SPA2 can be established to statistically significantly differ from the other two since the P-value of the comparisons is below the significance level of 0.05.

	Comparison	**P-value**
MPA	SPA1 - SPA2	0.665
	SPA1 - SPA3	0.000
	SPA2 - SPA3	0.000
MPB	SPA1 - SPA2	0.000
	SPA1 - SPA3	0.017
	SPA2 - SPA3	0.000
MPC	SPA1 - SPA2	0.000
	SPA1 - SPA3	0.112
	SPA2 - SPA3	0.001

Table 3.3: Results of the pairwise F-tests for each of the measurement points.

The results of the pairwise F-tests, shown in Table 3.3, are further visualized in Figures 3.15, 3.16, and 3.17, where the 95% confidence interval is shown for all platforms for each of the measurement points. Overlapping confidence intervals suggest that a statistically significant difference cannot be established between the datasets, whereas non-overlapping confidence intervals indicate a statistically significant difference between them.

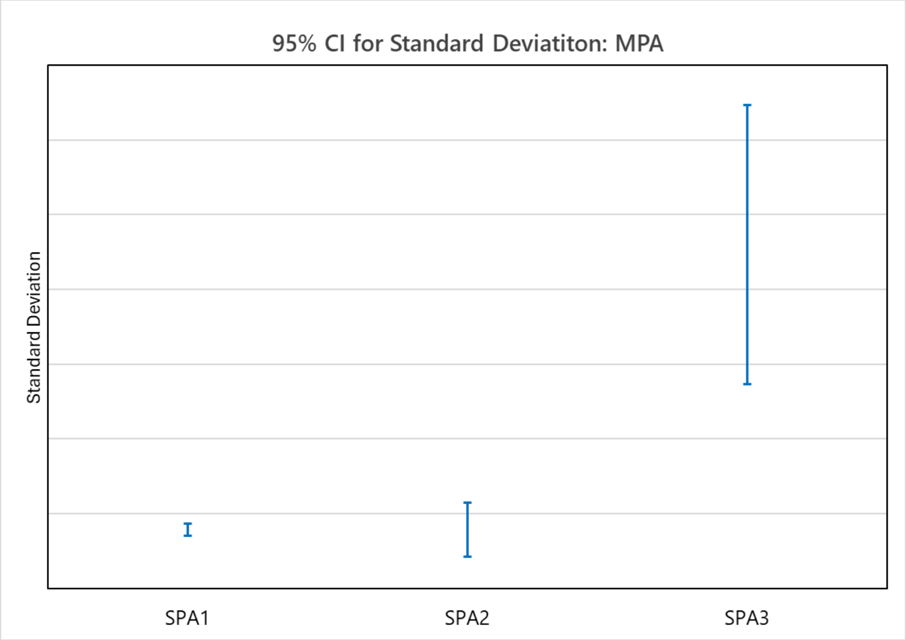


Figure 3.15: Confidence intervals for standard deviation MPA.

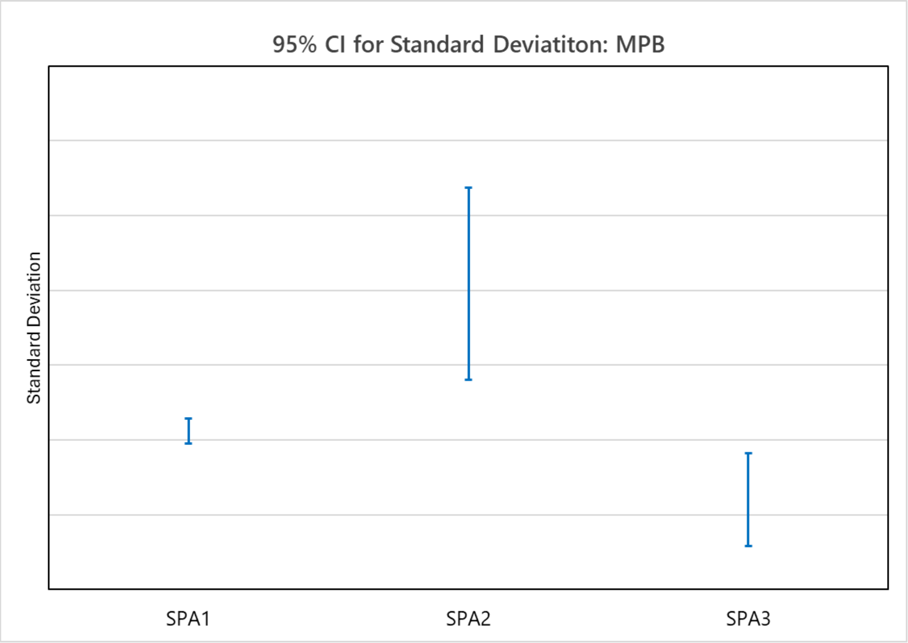


Figure 3.16: Confidence intervals for standard deviation MPB.

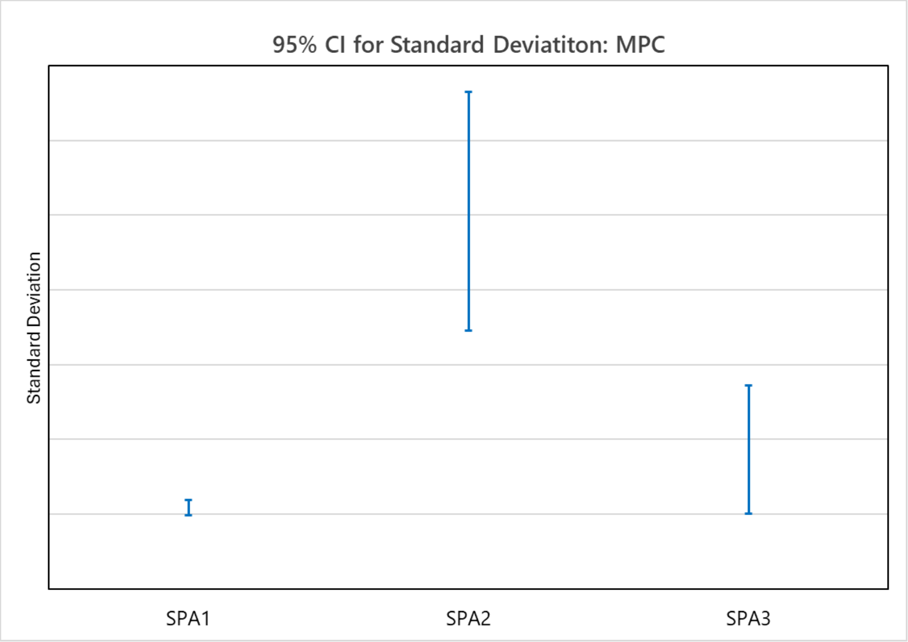


Figure 3.17: Confidence intervals for standard deviation MPC.

3.2.5 ANOVA

The Welch-ANOVA is performed to assess if there is a statistically significant difference between the means of the datasets for each of the measurement points. For these tests, the null hypothesis is that all means are equal and the alternative hypothesis is that not all means are equal. The results of the Welch-ANOVA can be seen in Table 3.4. For MPA, the test indicates that there is a statistically significant difference between the means of the datasets since the P-value is below the significance level of 0.05. For MPB, the null hypothesis cannot be rejected since the P-value is above the significance level of 0.05, implying that a statistically significant difference in means cannot be established. For MPC, the null hypothesis can be rejected since the P-value is below the significance level of 0.05, and thus a statistically significant difference between the datasets can be established.

Measurement point	**F-value**	**P-value**
A	346.71	0.000
B	0.93	0.409
C	79.28	0.000

Table 3.4: Result of Welch-ANOVA.

Further, the Games-Howell method is used as a post hoc test to the Welch-ANOVA to identify between which datasets a statistically significant difference in the means can be established. The null hypothesis for these pairwise tests is that the means are equal and the alternative hypothesis is that the means are not equal. The results of the Games-Howell tests can be seen in Table 3.5. For MPA, the mean of the dataset of SPA2 can be established to statistically significantly differ from the other two platforms since the P-values for the tests between SPA2 and the others are below the significance level of 0.05. No statistically significant difference can be established for the means of the datasets of SPA1 and SPA3 since the P-value is above the significance level of 0.05. For MPB, no statistically significant difference between the means of the datasets can be established since the P-values for all of the tests are above the significance level, which is expected considering the results of the Welch-ANOVA. For MPC, the mean of the dataset of SPA1 can be established to statistically significantly differ from the other two platforms since the P-values for the tests between SPA1 and the others are below the significance level of 0.05. No statistically significant difference can be established for the means of the datasets of SPA2 and SPA3 since the P-value is above the significance level of 0.05.

	Comparison	**P-value**	**Adjusted P-value**
MPA	SPA2 - SPA1	26.69	0.000
	SPA3 - SPA1	0.60	0.824
	SPA3 - SPA2	-4.98	0.000
MPB	SPA2 - SPA1	-1.33	0.392
	SPA3 - SPA1	0.30	0.952
	SPA3 - SPA2	1.35	0.377
MPC	SPA2 - SPA1	-7.58	0.000
	SPA3 - SPA1	-10.34	0.000
	SPA3 - SPA2	2.06	0.114

Table 3.5: Result of Games-Howell.

The results of the Games-Howell test, shown in Table 3.5, is further visualized in Figures 3.18, 3.19, and 3.20, where the 95% confidence interval is shown for all platforms for each of the measurement points.

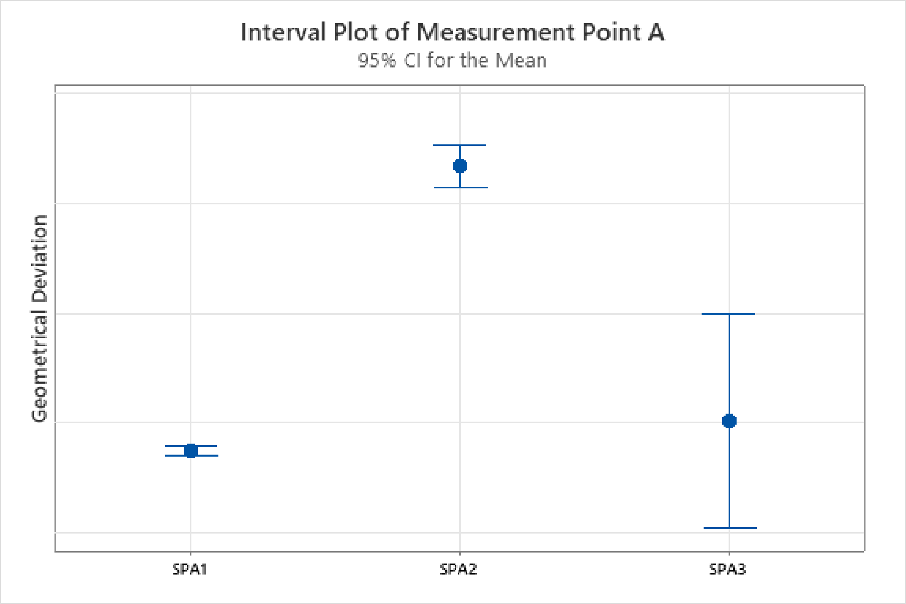


Figure 3.18: Confidence intervals for means MPA.

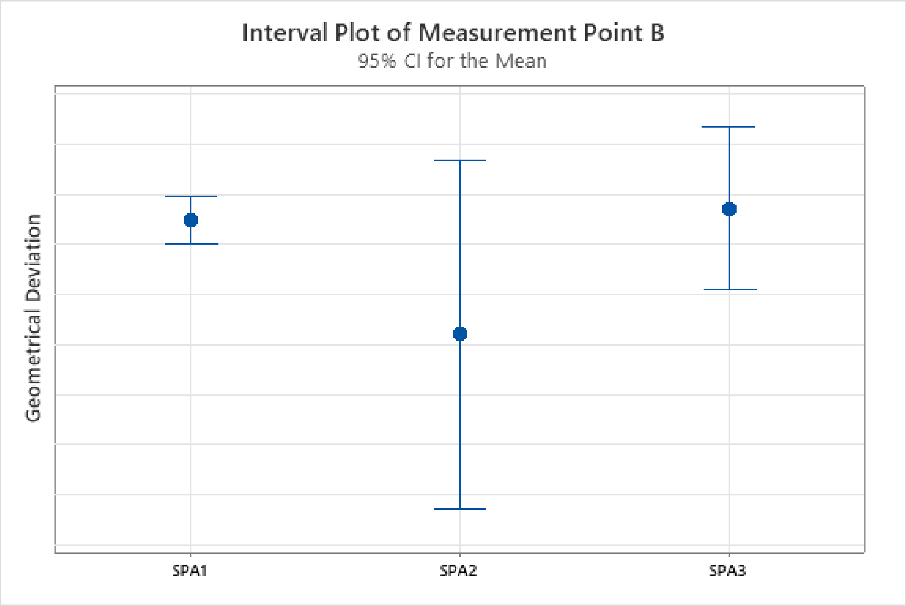


Figure 3.19: Confidence intervals for means MPB.

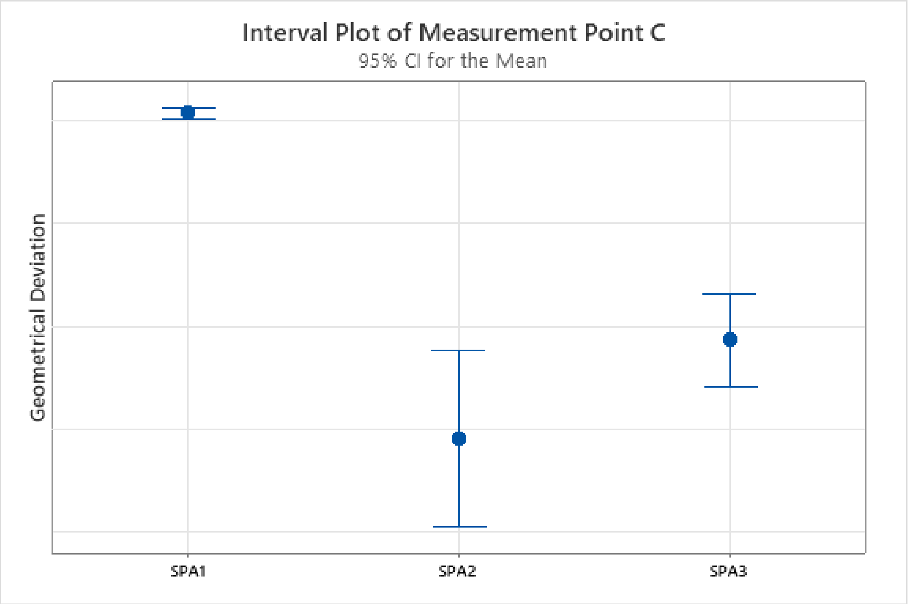


Figure 3.20: Confidence intervals for means MPC.

3.3 Discussion

In this section, discussion about the results of the statistical analysis of the datasets from the three platforms (SPA1, SPA2, SPA3) at three measurement points are presented. Limitations are highlighted and the results are discussed in relation to the first research question.

3.3.1 Measurement Point A

For MPA, the variation of the dataset for SPA3 could be established to statistically significantly differ from the datasets for SPA1 and SPA2. This was established using pairwise F-test as shown in 3.3. Further, this was visualized by the confidence intervals for the standard deviation in Figure 3.15, where it can be seen that the confidence interval for SPA2 does not overlap with any of the other two. This notion is furthered strengthened by observing the boxplots shown in Figure 3.6. Where the range and IQR of the dataset is higher for the SPA3 platform compared to the other two. Further, the difference in variance can be observed when analyzing the process performance, which can be seen in Figure 3.1. This shows that the dataset for the SPA2 platform has much lower Pp value, indicating that the variance of the processes is higher, in relation to the specification limits, compared to the other two platforms.

The Welch-ANOVA established that there is a statistically significant difference between the means of the datasets. Further, the Games-Howell method was used to establish that the statistical difference was between the dataset of the SPA2 platform and the datasets of the other two platforms. No statistically significant difference could be established between the datasets for the SPA1 and SPA3 platform. This is also visualized in Figure 3.18, where it can be seen that the 95% confidence interval of the SPA2 platform does not overlap with any of the other platforms and the intervals for SPA1 and SPA3 overlap. This notion is further strengthen considering Figure 3.6, where its indicated that the dataset for the SPA2 platform is shifted upwards compared to the other two, which have a similar location. Important to note when it comes to the mean of the geometrical deviation is that the direction of the deviation is considered, i.e. that the deviation is either positive or negative. This means that a statistically significant difference of the mean (when considering direction) could be established when the absolute deviation (not considering direction) is the same. This could be the case for MPA since the average deviation of the dataset for the SPA2 platform is positive (above the nominal value) and the average for the other two are negative (below the nominal value).

3.3.2 Measurement Point B

For MPB, it was established that the variance of all datasets statistically significantly differed from each other. By reviewing the boxplot shown in 3.7, all three datasets have different lengths of the IQR and the range, with SPA2 having the longest, and SPA3 having the shortest. This demonstrates a greater spread in SPA2, and a narrower spread of SPA3. By conducting the pairwise F-test, it was established that the variance of all datasets statistically significantly differed from each other. This was visualized by the 95% confidence intervals of the standard deviations shown in Figure 3.16. It can be observed that none of the confidence intervals overlap, indicating a statistically significant difference of the standard deviations. It can also be seen that SPA2 has the highest variance and SPA3 the lowest. This notion is also strengthen when analyzing the process performance. Where SPA3, has the highest process performance values and SPA2 the lowest, as can be seen in Figure 3.1. This implies that dataset of the SPA3 platform delivered values within the specification limits more consistently, because it had lower variance.

Further, its was established by the Welch-Anova and the pairwise comparisons that a statistical difference in the means of the datasets of MPB could not be found. This is visualized in Figure 3.20, where it can be seen that all three of the 95% confidence intervals overlap, indicating that there is no statistically significant difference. This can also be observed in Figure 3.7, where the IQRs are located similarly in relation to the specification limits. Because a statistical difference could be found in the variance of the datasets, but not in the means, the data is likely centered around a similar value, however the spread of the data is different.

3.3.3 Measurement Point C

For MPC, the variance of the dataset for the SPA2 platform was established to statistically significantly differ from the other two. This was established with pairwise F-tests. This is further visualized in Figure 3.17, where it can be seen that the 95% confidence interval for the standard deviation of the SPA2 platform does not overlap with the other two. It can also be observed that the confidence intervals of SPA1 and SPA3 is overlapping and therefore no statistically significant difference could be established between them. This conclusion is further supported by the boxplot of the datasets in Figure 3.8 which illustrates that the range and IQR for SPA2 is higher than the other datasets. This indicates that the dataset of the SPA2 platform has a higher variation than the other two. The notion that the dataset of the SPA2 platform has higher variation was further strengthened when analyzing the process performance, which can be seen in Figure 3.1. It shows that the SPA2 platform has a significantly lower Pp value than the other two, indicating that the variance of the dataset for SPA2 is higher, in relation to the specification limits, compared to the datasets for the other platforms.

The Welch-ANOVA established that there is a statistically significant difference between the means of the datasets. Further, the Games-Howell method was used to establish that the statistical difference was between the dataset of the SPA1 platform and the datasets of the other platforms. This is visualized in Figure 3.20, where it can be seen that the 95% confidence interval of the mean for the SPA1 platform does not overlap with any of the other two. The 95% confidence interval of the mean for the SPA2 and SPA3 platform overlaps, therefore no statistical difference can be established between them. This result is supported by Figure 3.8 where it can be observed that the dataset for the SPA1 platform is shifted upwards compared to the other two, which have a similar location.

3.3.4 Limitations

An initial insight drawn from the time series (see Figures 3.3, 3.4, and 3.5) is the difference in the amount of measurement points between the platforms. For SPA1, which is the oldest platform and has been in mass-production since 2014, there are significantly more data points compared to the other platforms. When comparing the datasets, this significant difference in sample sizes create an imbalance. Another concern is that a dataset of only 15 (SPA3) or 25 (SPA2) samples might not be able to reflect the full characteristics of these platforms simply because the dataset is too small. A consequence of this is that the uncertainty increases in the estimation of variance and mean value. This is due to several reasons. For example, larger deviations in a small dataset have a greater impact, than compared to the same type of deviations in a larger dataset. This could be seen in the confidence intervals for both variance and mean, where the intervals for the SPA1 platforms is significantly narrower than the other two. This indicates that there is more uncertainty in the datasets for the SPA2 and SPA3 platforms. The point is, in order to fully reflect a production process such as SPA2 or SPA3, it would be crucial to have a sufficient set of samples to be able to reflect the true characteristics of the process. Thus, having a sufficient set of samples would make the comparison between the platforms more reliable and robust.

Another factor that influence the results of the data analysis is that the platforms are in different stages of production. To clarify, the samples taken from both SPA1 and SPA2 are measured when the rear floors are being mass-produced. Thus, the platforms are fully developed for production. However, the SPA3 platform is still in the pilot-phase of production. Since this reflects production at a much lower scale, measurement values acquired at this stage might not reflect what would happen at a full-scale production. For the SPA3 platform, many of the processes are manual and tools and fixtures temporary, also process parameters are being adjusted to dial in the process. This is different from a full-scale production where all processes are established and most process parameters constant. Hence, comparing measurements from two different stages of production might not provide a fair assessment.

Since the samples for the different platforms have been collected from different manufacturing plants, further inconsistencies will influence the quality of the data. Two examples are the measuring devices used to collect the data with different measuring systems and different operators. Factors like these will increase the uncertainty of the data. Further, different routines have been used to collect the data. For the SPA1 platform, samples have routinely been taken out to the manufacturing line to be measured. In comparison, for the SPA2 platform the measurements of the platform have been in response to out of the ordinary events, such as changes to a fixture. This could explain why, for measurement point B and C, the dataset for the SPA2 platform performed worse than the other two.

3.3.5 Conclusion

The aim of this section was to establish if there is any difference in the geometrical quality outcome of the rear floor concepts: sheet metal floor (SPA1), mixed sheet metal/cast floor (SPA2), and fully cast floor (SPA3). Additionally, it aimed to characterize the nature of any identified differences. To investigate this, several statistical methods were carried out and the result is summarized below in Table 3.6.

		Difference in variance	**Highest variance**	**Difference in mean**	**Highest mean**
MPA	SPA1 - SPA2	No	-	Yes	SPA2
	SPA1 - SPA3	Yes	SPA3	No	-
	SPA2 - SPA3	Yes	SPA3	Yes	SPA2
MPB	SPA1 - SPA2	Yes	SPA2	No	-
	SPA1 - SPA3	Yes	SPA1	No	-
	SPA2 - SPA3	Yes	SPA2	No	-
MPC	SPA1 - SPA2	Yes	SPA2	Yes	SPA1
	SPA1 - SPA3	No	-	Yes	SPA1
	SPA2 - SPA3	Yes	SPA2	No	-

Table 3.6: Summary of Results.

Although statistically significant differences were established in the mean and variation between the datasets, this does not prove actual or practical differences in geometrical quality between the platforms, considering the limitations mentioned in Section 3.3.4. To draw clear conclusions regarding the practical differences in the geometrical quality outcomes of the different rear floor concepts, additional data is required, and the manufacturing and data collection must be made under consistent conditions.

4

Methods and Processes for Improving Geometrical Quality in Mega-cast Rear Floors

In this chapter, methods and processes for improving the geometrical quality will be mapped and their impact discussed. This will be done through literature study and interviews with experts in related fields. The methodology of the literature study and interviews are described in Section 4.1, the result are presented in Section 4.2 and the results are discussed in Section 4.3.

4.1 Methodology

The purpose of this section is to define the methodology and describe the methods used to answer the second research question, i.e. "How and to what extent can the geometrical quality of the mega-cast rear floor be improved?". The aim of the methodology is to identify, structure, and evaluate methods and processes to improve the geometrical quality of the mega-cast rear floor. Since the focus of this part is to uncover various alternatives for geometrical quality improvements and understanding their potential, a combination of in-depth understanding and a broad overview of the alternatives is needed. Hence, a qualitative research approach was deemed suitable and is utilized to achieve this. The methodology begins with an initial literature review, during which potential processes and methods for improving geometrical quality are examined. This is followed by a brainstorming session in which new search terms and potential processes are added to the literature review. Next, the potential processes and methods are categorized using an affinity diagram, which serves as a mediating tool for the interviews. After each interview, the affinity diagram is updated with new insights gathered from the interview. This iterative approach allows for identification of methods and processes to improve the geometrical quality, while also incorporating expert insights into the findings, thereby combining both breadth and depth in the research. Hence, this approach was deemed as suitable since it aligns with the principles of conducting qualitative research.

An overview of the methodology can be seen in Figure 4.1, the methods and their selection are further described in the subsequent sections. Additionally, an approach for analyzing the qualitative data is presented in Section 4.1.5.

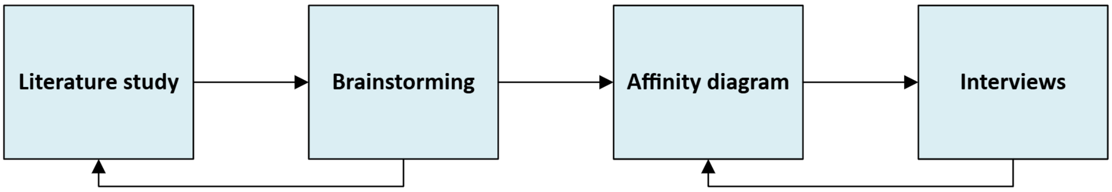


Figure 4.1: Flowchart of methodology for mapping processes and methods to improve the geometrical quality outcome of mega-cast rear floors.

4.1.1 Literature Study

The initial phase of mapping methods and processes to enhance the geometrical quality of mega-cast rear floors involves a literature review. The primary objective of this phase is to identify potential processes and methods, making the literature review inherently exploratory. Because the goal is to uncover various options rather than conduct an in-depth evaluation, the review prioritizes breadth over depth. The process of the literature study is visualized in Figure 4.2.

The literature review was carried out by searching in relevant databases using a range of keyword combinations. These combinations were either created by pairing keywords together, or using and/or operators. To broaden the search, different forms of word inflections were utilized. To exemplify, "mega casting" paired with "distortion" creates different combinations such as "mega casting distortion" and "mega casting distorted" by using a different word inflection. The initial search was supplemented by reviewing relevant sources cited within the retrieved articles, along with additional searches using new keywords derived from the initial findings. Further, after having conducted the brainstorming (see Section 4.1.2), the literature study was repeated to validate and explore options generated through the brainstorming.

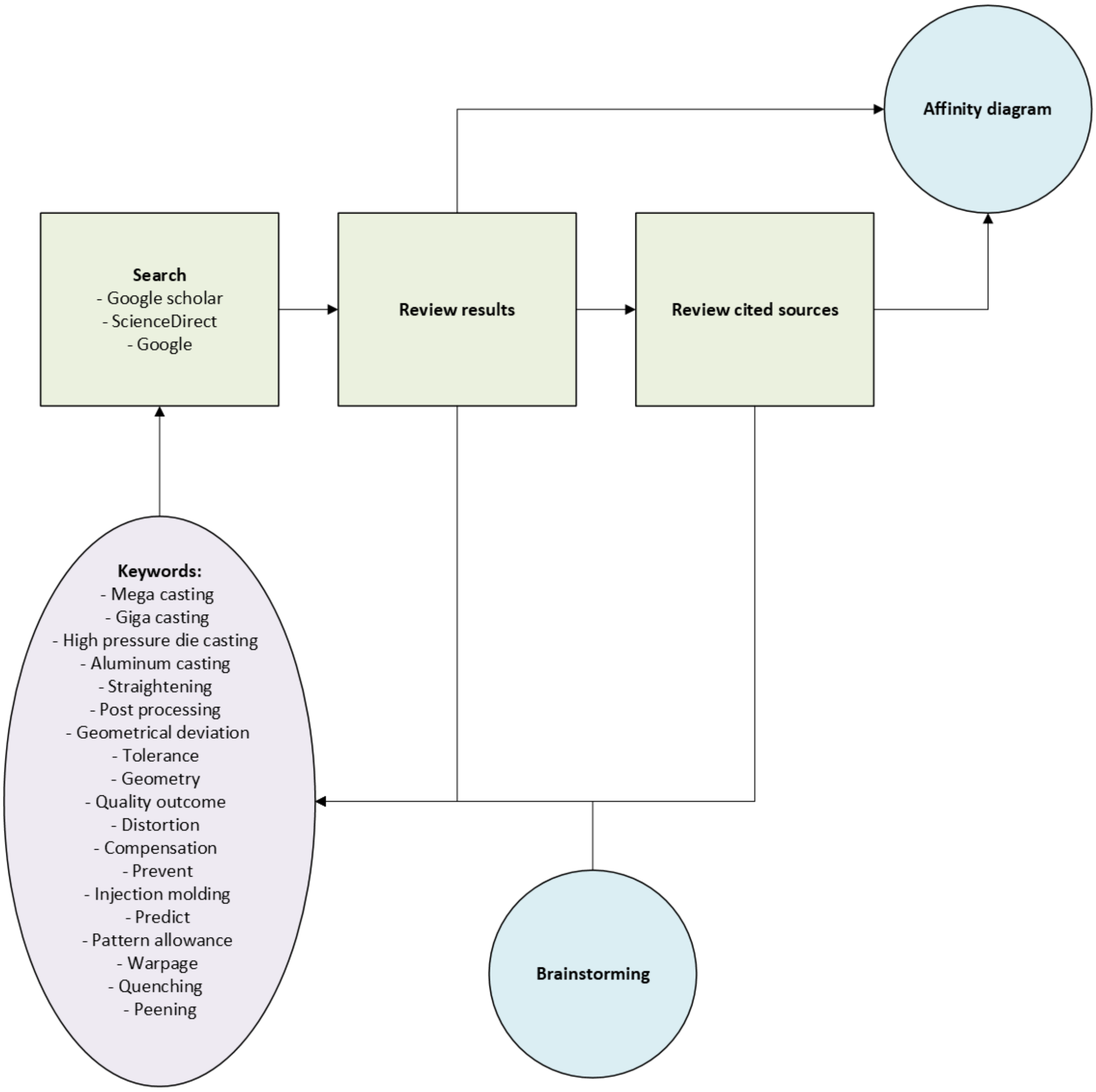


Figure 4.2: Flowchart of literature study process.

4.1.2 Brainstorming

Brainstorming is a collaborative method to generate ideas in order to find answers to a problem [27]. In the brainstorming session, key principles are to encourage unconventional or "out-of-the-box" ideas and to restrain immediate judgment [27]. The purpose of the brainstorming session is to identify innovative methods and processes that aim to increase the geometrical quality of the mega-cast rear floor.

The brainstorming session was initiated with an individual idea generation phase, during which time was given to generate potential solutions to improve the geometrical quality. The individual idea generations was followed by a collaborative idea generation to explore further options. All the gathered ideas were then evaluated and further developed through a thorough discussion. The focus of this discussion was the feasibility of the ideas in a real-world setting. If the idea was deemed to be feasible, it was documented. Subsequently, the documented ideas were further examined through reviewing relevant literature and external resources by utilizing academic databases, search engines, and other internet websites.

4.1.3 Affinity Diagram

Three commonly used visual mapping strategies are: mind maps, concept maps and cognitive maps, which are all useful in illustrating patterns of research findings [28]. In [29], another visual technique is presented, affinity diagrams, which is a procedure that can be used to structure and make sense of unstructured qualitative data. The method works by clustering similar options together until groups are formed then the groups/categorize are defined [30]. The affinity diagram was considered to be the most suitable visualization technique to organize and structure the gathered options and group them into clusters.

4.1.4 Interviews

In [31], interviews are mentioned as one of the most common methods used for qualitative data collection. Additionally, [31] describes three main categories of research interviews: structured, semi-structured, and unstructured. Structured interviews are based on predefined questions asked to the respondent, with no opportunity for follow-up questions to responses that require further clarification. On the other hand, unstructured interviews are conducted without any predefined structure or well-defined questions. Such an interview can be guided by an opening question and an initial response, making it suitable for situations where there is limited knowledge about the topic. Semi-structured interviews are guided by a set of predefined questions designed to examine key areas within the topic and enables an opportunity for the interviewee to elaborate on the response.

The aim of this stage is to get expert input on suggested methods and processes, such as understanding their feasibility and challenges, as well as exploring other possible solutions. To achieve the aim, the interviews require a set of predefined questions and must allow for an open discussion between the respondent and the interviewer to explore other potential methods. Thus, a semi-structured approach was chosen as a suitable method.

An interview guide is an important tool that heavily influence the outcome of interviews [32]. A framework for developing an interview guide for a semi-structured interview is presented in [32]. The first step is to identify the prerequisites for using semi-structured interviews, with the aim of determining their suitability for the study. The second step is to retrieve and use previous knowledge, with the aim to acquire a comprehensive understanding of the subject. The third step is to formulate a preliminary interview guide, utilizing previous knowledge. The questions in the interview guide should be clearly worded, open-ended, non-leading and, participant-oriented to achieve the richest possible data. Further, the questions should consist of two levels: main themes and follow-up questions. The next step is to pilot-test the interview guide to confirm the coverage and formulation of the questions. This can be done both internally (within the research team) and externally by getting feedback from individuals outside the research team. The last stage of the framework is to present the interview guide, with the goal of having produced a clear and logical framework for semi-structured interviews.

The framework described above was applied to the development of the interview guide used for the expert interviews, the interview guide can be seen in Appendix A. The second stage of the framework was carried out through a literature review (see Section 4.1.1). The initial interview guide was formulated using the guidelines in step three of the framework. The pilot-testing included both internal testing and external feedback from supervisors.

The selection of participants for the interviews was aimed at finding interviewees from a variety of fields related to the subject. There are a variety of sampling strategies that can be applied to selecting interviewees for a qualitative study. To accomplish the goal of the selection, a combination of quota sampling strategy and convenience sampling was selected. Quota sampling is a purposive sampling technique in which the population is divided into distinct categories, and samples are taken from each category [33]. For every category, a specific quota of samples must be collected, ensuring that each category is adequately represented in the data [33]. For selecting participants in each of the categories convenience sampling was used. Convenience sampling, unlike random sampling, is not entirely random because it takes into account factors like proximity and willingness to participate when selecting participants [33]. In practice this meant that, for example, experts from both industry and academia were approached to gain a more comprehensive understanding and diverse perspective of the task. In addition, to the largest extent possible, multiple interviewees within the same field were interviewed to confirm and validate the results of the interviews. Further, snowball sampling was used to identify new interviewees by obtaining referrals from participants in previous interviews.

For the interview procedure, the interviews were conducted either physically, or via an online-meeting and spanned between 30-60 minutes. All interviews were either audio- or video-recorded (with granted consent) and transcribed. Notes were also taken during the interviews to capture the most important points. The interview procedure followed the semi-structured guide shown in Appendix A.

4.1.5 Qualitative Analysis Approach

In [34], five methods for qualitative data analysis are suggested. In the following list, each of the methods is briefly explained along with its appropriate application.

1. Content Analysis - Aims to analyze textual data by categorizing information to find common patterns. This method is especially useful when the goal is to gain a comprehensive understanding of the topic.
2. Narrative Analysis - Aims to focus on the narratives of the interviewee such

as their experiences and perspectives. This method is useful when there is interest in gathering information about interviewees' motivational drivers and life experiences.
3. Discourse Analysis - Aims to understand the linguistic and rhetorical techniques of the interviewee. This method is suitable when there is an interest in exploring e.g. assumptions and biases of interviewees.
4. Thematic Analysis - Aims to identify patterns or themes within the collected data based on the principle that they will emerge naturally. It is in an inductive approach suitable for examining both the breadth and depth of the data.
5. Grounded Theory Analysis - Aims to collect new theories and models, based on the principle that the theories will emerge naturally throughout the data collection process. This method is particularly suitable when the goal is to explore an unknown field.

For the qualitative study, the aim is to identify methods and processes to improve the geometrical quality of the mega-cast rear floor, as well as gather expert input on these methods. Therefore, a comprehensive understanding is needed for the suggested solutions. Furthermore, there is a need to structure and categorize the identified methods to provide clarity in the findings and asses them from an expert view. A key principle of thematic analysis is to be open-minded and carry out the work process iteratively, updating the thematic framework when new information has been provided [34]. Therefore, a thematic analysis was deemed as an appropriate qualitative analysis approach to structure the collected data within appropriate themes (with the help of an Affinity Diagram, see Section 4.1.3). Further, elements of content analysis were incorporated and combined with the thematic approach to further deepen the understanding of the data and gain a more comprehensive view of the identified methods and processes.

4.2 Results

In this section, the results of the literature study and the interviews are presented. In Section 4.2.1, an overview of the methods and processes identified through literature study and interviews are presented. In Sections 4.2.2 to 4.2.7 the results from the interviews are explained in detail in relation to the corresponding category.

4.2.1 Overview of Methods and Processes

The methods identified in the literature study can be seen in Figure 4.3. This affinity diagram was used as a mediation tool in the subsequent interviews.

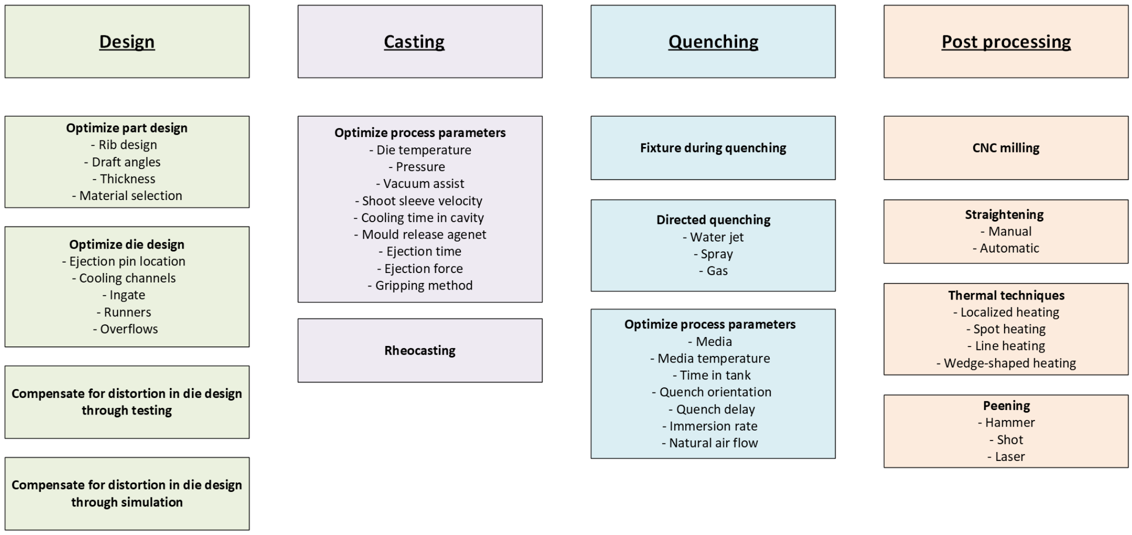


Figure 4.3: Initial affinity diagram from literature study.

Interviews were conducted with 14 respondents, as shown in Table 4.1. In the subsequent sections the respondents will be referred to their respondent order code.

Respondent Order	**Area of Expertise**	**Respondent Title**
R1	Geometry assurance & Robust Design	Geometry System Developer
R2	Structural Materials	Technical Leader
R3	Mechanical Properties & Aluminum Casting	Professor - Engineering Materials
R4	Geometry assurance & Robust Design	Professor - Product Development
R5	Geometry assurance & Robust Design	Geometry Assurance Analyst
R6	Casting	Assistant Professor - Materials and Manufacturing
R7	Casting	Senior Lecturer - Materials and Manufacturing
R8	Mechanical Properties & Materials	Advanced Engineering Leader
R9	Casting Simulation	Doctoral Student - Product Development
R10	Casting Simulation	Mechanical Engineer
R11	Mega-casting	Senior Area Leader
R12	Mega-casting	Manufacturing Engineer
R13	Mega-casting	Senior Casting Engineer
R14	Mega-casting	Technical Specialist

Table 4.1: List of interviewees.

The interviews in combination with the literature study resulted in a final affinity diagram of identified methods and processes which can be seen in Figure 4.4.

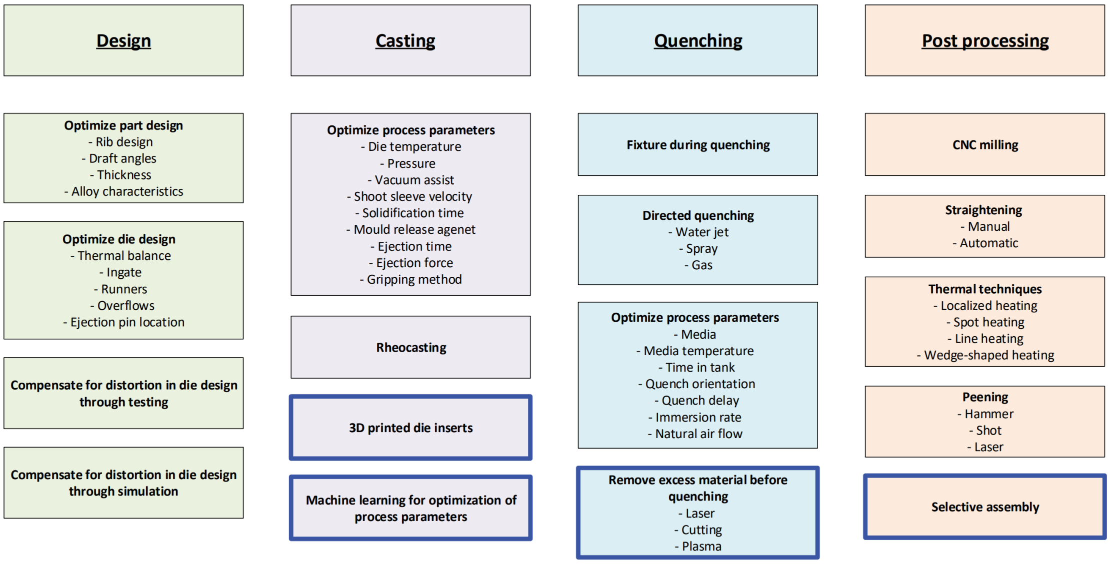


Figure 4.4: Overview of methods and processes for improving the geometrical quality of mega-cast rear floor (additional findings from the interviews are marked with a blue frame).

The methods and processes in Figure 4.4 are briefly defined below:

Optimize part design: This method involves optimizing the design of the part for geometrical quality. For example, this involves design parameters such as ribs, angles, and thicknesses.

Optimize die design: This method refers to optimizing the design of the casting die for geometrical quality. Examples of design parameters that can be optimized are thermal balance, ingate, runners, overflows, and ejection pin location.

Compensate for distortion in die design through testing: This method refers to changing the die design to a non-nominal geometry, which counteracts the distortion of the part. This is done with the aim that after the part is distorted, it will achieve the nominal geometry. In this method, the deviation from the nominal geometry is established by doing physical tests of the casting and measuring the distortions.

Compensate for distortion in die design through simulation: This method refers to the same principle of compensating the die design as mentioned above, but instead of establishing the deviation from the nominal geometry through physical tests it is done through simulation of the casting process.

Optimize process parameters (casting): This method refers to optimizing the parameters of the casting process for geometrical quality. Examples of process parameters that can be optimized for geometrical quality are die temperature, solidification time, and pressure.

Rheocasting: Rheocasting is a manufacturing method similar to HPDC but instead of using a melted alloy, it uses an alloy slurry in a semisolid state. This manufacturing method operates at lower temperatures, which could potentially reduce shrinkage and distortions of the castings.

3D printed die inserts for complex cooling: This method refers to the utilization of additive manufacturing for producing die inserts for the mega-casting process. This technology could allow for intricate cooling channels and customized material processes that cannot be achieved with traditional manufacturing processes. This can allow for better thermal balance of the die and thus improve the geometrical quality.

Machine learning for optimization of process parameters: This method involves utilizing machine learning to optimize the process parameters of the casting. The method includes online measurements of the casting which feed information to the machine learning algorithm, enabling real-time adjustments to the process parameters.

Fixture during quenching: This method involves using a fixture during the quenching to mechanically constrict the casting. A lot of distortion occurs during the quenching process, therefore by constricting the casting with a fixture the distortion can be reduced.

Directed quenching: This method refers to a quenching process where instead of lowering the casting into a tank, the casting is sprayed with jets of water or gas. This allows for a more controlled quench, where the jets can be directed at specific areas to cool them faster, with the intent of reducing the distortion.

Optimize process parameters (quenching): This method refers to optimizing the quenching process parameters to improve the geometrical quality. Examples of process parameters that can be optimized are media temperate, time in tank, and quenching orientation.

Remove excess material before quenching: This methods involves removal of excess materiel, such as runners, biscuits, and overflows, of the casting before quenching. The excess material can be removed by various cutting operations such as trimming, plasma cutting, and laser cutting. The goal of this is to increase the geometrical quality by removing thick areas to avoid tensions and shrinkage and facilitate a more uniform cooling.

CNC milling: This post-processing method involves correcting the casting by removing material through CNC milling. This can be used to reduce the variation of the casting and improve the geometrical quality.

Straightening: This post-processing method involves deforming the casting to contract any distortion and return it to its nominal geometry. It can be done manually for example, by using fixtures and hydraulic tools that can bend and twist the casting or through hammering. It can also be done with an automatic straightening machine that iteratively measures and straightens the casting into its nominal shape. The sequence and force of the automatic straightening operations can be established from the measurements utilizing a machine learning algorithm.

Thermal techniques: The thermal techniques mentioned are typically used to correct and prevent distortions caused during a welding process. The treated area is heated locally to induce stresses. Upon cooling, the distorted area is then pulled back to the desired shape. Although the main are of use might be a different context, it could be an alternative to correct local distortions in other contexts.

Peening: Peening is a process where the surface of a part is locally struck in iterations which can be done in several ways. Some examples of peening techniques are hammer peening, shot peening, and laser peening. The main purpose of such methods is to improve the mechanical properties of the material by inducing stresses locally which can enhance e.g. resistance to wear and tear. Such methods can also be used to correct distortions, although this is not the main use of application.

Selective Assembly: Selective assembly is an assembly strategy where parts are initially measured with respect to their tolerance values. Based on this measurement, the parts can then be matched with mating components that offset any geometrical deviations during assembly. This strategy could be suitable for sheet or hybrid metal assemblies. However, it cannot be applied to fully casted parts, though it could still be useful for later stages of assembly.

4.2.2 Design

A recurring theme in the majority of the interviews is that the design phase offers the greatest opportunity for impactful changes. Compensating for distortion is the most frequently discussed approach to improving the geometrical quality of the mega-cast rear floor. This compensation can be achieved through two main methods: physical testing and simulation. All respondents agree that compensating for distortion through simulation, before any dies have been manufactured, would be the preferred method, as it reduces lead time and minimizes costs. However, compensating through simulation requires accurate simulations, and multiple respondents note that achieving enough accuracy in simulations are challenging. Furthermore, R11 argues that the robustness of simulations could be problematic due to varying process parameters in the foundry. For example, R11 points out that temperature fluctuations in the foundry and changes in quenching water throughout the year could cause simulations to be inaccurate, making compensation ineffective.

Considering the challenges with simulation-based compensation, respondents also mention physical testing as an alternative. However, as R8 explains, compensating through testing is costly, and without accurate simulations, there is uncertainty about its effectiveness. This concern is raised by multiple respondents, who also highlight that the high cost of modifying already manufactured dies is one of the major drawbacks of this approach.

A majority of respondents mention optimizing die and component design as a viable option for improving the geometrical quality of the mega-cast rear floor. R10 and R13 note that many design elements, such as ribs and thickness, significantly impact geometrical quality. Additionally, R8, R10, R12, and R13 emphasize that thermal balance in die design is a crucial aspect that should be optimized. Further, R13 explains that solidification pattern is something that have a large impact on the distortions and thus should be optimized for in die design. Multiple respondents express that making design changes earlier in the product realization process is considerably less expensive and complex than making changes at later stages. Therefore, optimizing the design before manufacturing expensive tools is the preferred approach. However, several respondents point out that the main challenge in optimizing the design lies in the need for better knowledge and accurate simulations.

4.2.3 Casting

The casting process itself is identified by multiple respondents as a contributor to the geometrical deviations and can thus be optimized to improve the geometrical quality. R8 notes that there are a large number of process parameters in the casting process which makes it time consuming to optimize manually. However, R12 and R13 identifies thermal balance of the die and solidification time as two of the most impactful process parameters to optimize in regards to the geometrical quality. Further, R10 notes that longer solidification time in the mold could reduce distortions. However, some respondents mentions that is difficult to increase the solidification time due to cycle time limitations. Additionally, R14 notes that the casting process is optimized for high casting quality, leaving very little room for further optimization in terms of geometrical quality.

Rheocasting is mentioned by R2 and R7 as a manufacturing method that potentially could improve the geometrical quality of the rear floor due to its lower temperature, which results in less shrinkage. However, as R6 points out, rheocasting is a new and unproven technology. Therefore, there are considerable risks involved in implementing such an immature technology. The general consensus among respondents is that while rheocasting holds promise for the future, it is not yet mature enough to be implemented for large structural castings.

R2 and R8 also mention that additive manufacturing can be used to produce casting dies, enabling the creation of more intricate and complex cooling channels. R13 identifies that with traditional manufacturing technologies, the cooling channels have to be straight which limits their functionalities. R8 further highlights that additive manufacturing technology allows for cooling channels to be placed closer to the die's surface, improving thermal optimization. Additionally, R2 notes that additive manufacturing could facilitate the development of advanced and customized material properties in the die.

4.2.4 Quenching

The quenching process is believed by most respondents to be one of the stages in which the most distortion occurs. Hence, it is also considered one of the stages with the highest potential to improve the geometrical quality by improving the quenching process. One recurring topic when discussing methods for improvements regarding the quenching process is to perform simulations. Most respondents believe that performing simulations is crucial in connection to implementing methods for improvements. To exemplify, R2 mentions that simulations can help understand the quenching process better and thereby it could, for example, be calculated how to orientate the part during quenching. Many respondents also point out the importance of simulating the quenching process to predict residual stresses since such stresses, if too high, could lead to plastic deformation and in worst case cracks.

Having a fixture during the quenching process is one of the most promising methods according to most respondents. The general view is that this alternative is cheap and easy to implement. R5 compares having a fixture during the quenching process with other methods such as straightening and compensation of the die, and states that the fixture method is a much cheaper alternative. R8 highlights another advantage with the method which is that it is flexible and can be adjusted to handle a lot of variation in the casting process. However, several respondents highlight the challenges of this method. R5, R8, and R11 all agree that it could increase the processing time and thereby it is a challenge to perform the quenching fast enough. Another concern brought up by many respondents are residual stresses occurring during quenching which could have an impact on material properties. The concern is that if the residual stresses are too high, it could lead to plastic deformation and cracks in the part. However, the general consensus among the respondents is that the stresses should not reach levels where this would occur. In connection to this, R1 explains that too high residual stresses might also lead to failure of crash tests. Further, R8 brings up another challenge which is that when the part is clamped during fixture, deformation might occur in other areas than the legs.

Directed quenching is considered by several respondents to be an interesting idea. R3 explains that by having a more controlled quenching process where some areas are cooled more rapidly the distortions can be controlled and reduced. This can be done through utilizing water jets. However, many respondents believe that directed quenching methods would present several challenges. R5 brought up that water jet quenching could be an alternative, however it would require a lot of time to cool the part. In connection to this, R5 also mentioned that when it comes to distortions, even if the part is cooled down slowly, distortions can happen anyway and hence there is no difference in cooling slowly or rapidly. Further, R10 mentions that gas quenching will not entail good mechanical properties and that the process is too slow.

Several respondents mention optimizing process parameters as an alternative for improving the geometrical quality. R6 explains that some parameters may have a greater impact than others, giving the example that parameters such as orientation and time in the tank offer room for optimization, while parameters like quench delay have limited potential for improvement. R13 elaborates on the quenching orientation by describing that the angle of the quenching is important to avoid air pockets and ensure uniform cooling. R13 also mentions that a main contributor to distortion is the media temperature. Further, R6 and R10 emphasize the importance of optimizing quenching process parameters through simulations, which, for example, could predict the rate at which the temperature drops during quenching.

Many respondents mention removing excess material before quenching as another alternative. R6 suggests cutting off the gating before quenching, as this could be beneficial due to the high temperatures of the gate and biscuit. By doing so, there may be less residual stress in the part, which could result in lower distortion during quenching. R10 and R13 describe the issue of residual stress, explaining that the ingate pulls on the part during quenching. Therefore, removing the gating earlier would reduce stress during the process. However, R11 and R13 point out that cutting off the gating before quenching adds complexity and introduces new challenges, such as the potential for sticking during hot trimming. To address this, pre-treatment of the part, such as lubrication, could be necessary.

4.2.5 Postprocessing

The general view among the respondents is that post-processing alternatives are challenging to implement because they are expensive (both in terms of investment and running cost), add cycle time, and require additional space in the foundry. These presented challenges are brought up by several respondents.

The most well-known and discussed method for the post-processing theme is straightening. Some respondents addresses challenges and risks in the straightening method. R3, R8, and R10 all mentioned that there could be a negative impact on the material properties. R8 elaborates on this and mentions that by straightening the part, it undergoes plastic deformation and depending on how much the part elongates, the material properties can be weakened locally. In return, in such areas, fracture is more likely to occur in a crash. Further, R3 mentions that the ductility of the material can be worsened by mixing recycled and non-recycled material, which in return can lead to damages during straightening. R1 and R11 express similar risks, where both respondents question how much of the material that can be bent before it cracks. Another challenge is brought up by R12 and R13 who explain that a straightening system need to be managed and maintained, and could also require additional staff training and the acquisition of special competence, which would increase cost.

Further, R5 and R11 mention that straightening is the most common technique used by top suppliers. R11 expresses that introducing an automatic straightening system makes sense from a manufacturing point of view and makes several arguments to support this. For example, by introducing such a system, the scrap levels can be reduced as well as the spread of the geometrical deviations. Thereby, the entire process of producing mega-cast rear floors could be easier. However, most respondents believe that an automatic straightening system would require a significant investment cost. Further, R11 notes that manual straightening could be a viable option for factories where the labor cost is low. However, in countries with higher labor cost, an automatic straightening system is a better option.

For CNC-milling, general reasoning among some respondents is that more material needs to be added to the part and then removed. Although this could be an alternative, the general perception is that it is one of the worst options since it decreases material utilization and adds more steps in the production. Some respondents also mention that such a process can worsen the material properties, when removing the casting skin.

A common view among the respondents for both thermal techniques and different peening methods, is that such alternatives are often used for other purposes and in other contexts. R2 mentions that thermal techniques are a common way to use in connection to welding to correct the geometrical deviations. R6 also points out that it is a way to introduce local material properties. R9 mentions that post heat treatment is not a simple process and also difficult to implement in a series production. Further, for the peening methods, R2 and R3 mention that such processes can be used to improve the material properties locally. For example, R3 mentions that it can for example be used to reduce the risk of cracks, rather than to correct geometrical distortions. Further, R9 expresses some risks with the peening methods and mentions that it might be difficult to implement due to the complexity and size of the mega-cast part.

4.2.6 Simulation

A recurring theme among most respondents is the importance of simulations. As mentioned earlier, many methods for improving geometrical quality rely on accurate simulations. As noted by R2, optimizing die design depends on precise thermal simulations. Both R2 and R5 emphasize that accurate simulations are essential for compensating die design for distortion, as without them, it is unclear whether the design will work or how much compensation is needed. Furthermore, R3 mentions that accurate simulations are necessary to optimize the quenching process and enable more complex and controlled quenching.

R10 explains that achieving accurate simulations is challenging. Both R7 and R10 identify accurate material data and simulation time as key challenges in simulating the mega-casting process. Additionally, R9 and R10 highlight meshing as another difficulty when dealing with these complex and large models. To achieve high accuracy, a very fine mesh is required, but this significantly increases both complexity and simulation time.

4.2.7 Online Measurement

Another observed theme is the integration of online measurements for the parts. The addition of online measurement can be utilized in various ways. R1 and R8 note that online measurements can provide data that can be fed back into the casting and quenching processes to optimize process parameters. They also mention that process parameters can be optimized through machine learning or AI, using the online measurement data as input. R8 emphasizes that this integration is necessary, as there are 120 process parameters, and manually testing them is challenging.

R4 and R5 highlight that selective assembly can benefit from online measurements. By measuring all castings, parts can be matched with mating components that offset any geometrical deviations. R4 suggests that this approach could be a cost-effective solution, as it would lower the manufacturing process requirements while improving the geometrical quality during assembly. However, R4 also notes that this concept presents many challenges, requiring changes to the entire manufacturing process, and might not be applicable for another five to ten years.

4.3 Discussion

In this section, the results from the literature study and interviews are discussed. Throughout the interviews, several reoccurring themes were identified which require further exploration. These topics are therefore analyzed in the following discussion.

4.3.1 Impact of Simulations

As described in the Section 4.2, one recurring theme throughout the interviews is simulations. Today, performing accurate simulations are challenging which brings uncertainty in the reliability of the simulation results. This presents a problem since simulation results influences many areas of the mega-casting process. As discussed in the interviews, simulation can be utilized in every stage of rear floor product realization process, from design to post-processing. Therefore, by having high reliability in simulation results, manufacturers can make more informed production process development decisions which in return are more likely to have a successful outcome. To exemplify, the design of the rear floor could be optimized early in the process, the most efficient settings for process parameters could be identified, and optimal conditions for the quenching process could be determined. As a result, the development lead time and costs could be reduced. Furthermore, by fine-tuning other stages of production prior to post-processing, the need for post-processing alternatives may be eliminated entirely.

Further, when it comes to geometrical quality improvement methods, there is a risk in today's context of investing in alternatives that heavily rely on the accuracy of simulation results, such as die compensation through simulation. This risk arises from the uncertainty in simulation results, as previously mentioned. Hence, making quality improvement decisions based on simulation results are difficult to motivate.

Therefore, it is crucial to improve the accuracy of simulations to increase the reliability in the simulation results so that quality improvement decisions can be made with greater confidence and lower risk. However, as discussed in the interviews, this is a particularly difficult challenge to tackle. To address this challenge, there will have to be an investment in resources to support the simulation process. This could e.g. be further investments in both software and hardware to increase computational power which would result in faster simulation runs, as well as investments to increase the competence and expertise in performing the simulation runs.

4.3.2 Extent of Quality Improvements

Further, one notation is that some methods and processes have high uncertainty when it comes to the extent of geometrical quality improvements. As mentioned, to compensate the die through simulations is highly dependent on that the simulations generate accurate and reliable results. Since the current state of simulations is not completely accurate nor reliable, it becomes challenging to assess the extent of quality improvements. Therefore, this creates a challenge in justifying the implementation of such methods in today's context.

However, other methods such as straightening presents a more certain outcome when it comes to what extent the geometrical quality can be improved. To clarify, an automatic straightening system will measure and straighten the part locally in those areas where the deviation from the nominal value are outside the tolerance limits. This is an iterative process that is ongoing until the deviations are within tolerance limits. Hence, with this method, the extent of quality improvements is easier to assess. However, as mentioned in Section 4.2, there are other drawbacks to this method, for example investment cost, increased cycle time, additional maintenance, as well as a possibility to negatively impact the material properties. Therefore, considering all these factors, it adds complexity to the decision-making process of quality improvement methods to prioritize and invest in.

4.3.3 Systematic Deviation versus Variation

The geometrical deviation can be divided into two types, systematic deviation and variation. The systematic deviation refers to a shift of the mean of the process compared to the nominal value, and variation refers the spread of the process. The different process alternatives for improving the geometrical quality can thus aim to improve either of these aspects of the process. Therefore, comparing some of the process alternative against each other is difficult since they aim to improve different aspects. For example, the compensation of the die only aims to remove the systematic deviation of the casting and wouldn't have any measurable impact on the variation of the process. While some other methods like optimizing the process parameters can reduce the variation of the process. Other processes like straightening have potential to significantly reduce both the systematic deviation and variation of the process.

Comparing the impact or value of reducing either systematic deviation or variation could be difficult. For a process with a certain process characteristics the impact of reducing the systematic deviation might dramatically reduce the number of parts that are outside of the specification limits. However, for another process the effect of reducing the variation of the process might have a larger impact than reducing the systematic deviation. Therefore, the process characteristics need to be analyzed in order to evaluate which process improvements are most suitable.

4.3.4 Timing of Improvements

Another interesting aspect discussed by the respondents related to the cost of alternatives for improving geometrical quality, is the timing of their implementation. The general insight, which may seem obvious, is that as the product realization process progresses, the cost of making changes increases. This fact makes many process improvements expensive to implement when the manufacturing process is established and the part design is finalized. However, in a project where the manufacturing process is not yet established, and the part design not finalized, the same process improvement can be significantly cheaper.

This becomes especially apparent when considering compensating the die design for distortion. If the compensation can be predicted through simulation, the die can be designed with respect to the expected distortion. Hence, the cost of compensating the die during the design phase is virtually non-existent. However, if compensation occurs after the die has already been designed and manufactured, the cost becomes substantial. This is true for many process alternatives that require changes to the manufacturing process or the design.

This observation further strengthens the notion that accurate simulation is crucial. If simulations can reliably predict the casting process, many process alternatives can be implemented at a significantly lower cost when introduced earlier in the process. However, this raises the issue of verifying the accuracy of a simulation without a fully functioning manufacturing process to compare with. It could be argued that it is difficult to trust the accuracy of a simulation without a physical manufacturing process to validate it. Therefore, the concept of predicting distortion and compensating for it in the die design before the physical manufacturing process is operational may not be feasible in practice. However, for projects where the same or similar parts are to be manufactured in multiple locations or manufacturing lines, simulation can be validated using the first manufacturing line. Hence, the subsequent manufacturing lines can then utilize simulation at an earlier stage with greater confidence and lower risk.

4.3.5 The Future of Quality Improvements

Some methods and processes discussed by the respondents are technologies that are still in their early stages of development and have yet to be fully proven in connection to casting. Among these are rheocasting, additive manufacturing, selective assembly, and the use of artificial intelligence and machine learning. The common view among the respondents is that all of these technologies have great potential in improving the geometrical quality of the mega-cast part. However, the fact that they are new and unproven makes the outcome of implementing these methods highly uncertain. The issue here is that high uncertainty entails high risk, leading manufactures to question whether the potential benefits outweigh the associated risks. Consequently, despite the promising aspects of these technologies, the risk may be deemed as too high, implying that the investment is difficult for manufacturers to justify. For these new and unproven technologies to gain wider acceptance, an early adopter must take the initiative and demonstrate their potential to the rest of the industry. Until then, their true potential cannot be assessed. However, this requires an investment in both time and resources which could be very costly. Ultimately, the decision to adopt such technologies will depend on whether organization perceive the potential benefits as outweighing the risks and investments involved.

4.3.6 Conclusion

The aim of this section was to establish how and to what extent the geometrical quality of the mega-cast rear floor can be improved. The results indicate that multiple methods and processes have the potential to improve the geometrical quality. These methods are linked to different aspects of the product development process, such as design, casting, quenching, and post-processing. A summary of these methods and processes is provided in Figure 4.4 and detailed in Section 4.2.1. A summary of the most promising methods considering a range of factors discussed in the interviews, for example feasibility in series production, extent of quality improvement, and cost, is provided below in Figure 4.5.

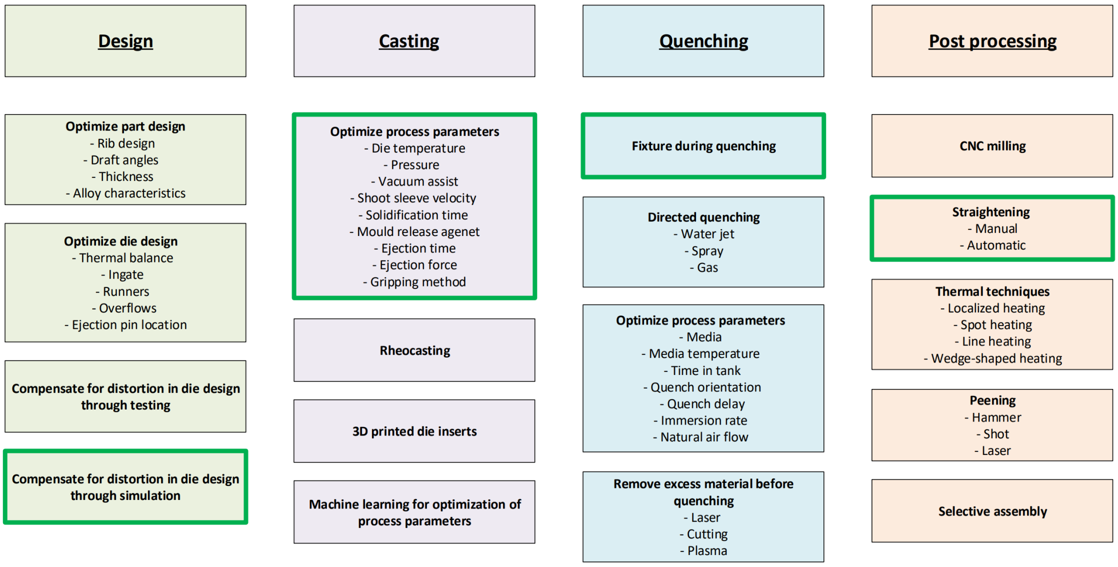


Figure 4.5: Most promising methods (marked with a green frame).

Further, the extent of how much the geometrical quality can be improved varies between methods and is influenced by specific prerequisites. For parts with distortion in particular areas, some methods may be more suitable for implementation. Additionally, some improvement methods entail a higher degree of uncertainty, while others present lower levels of uncertainty. As a result, assessing the potential for geometrical quality improvements is a complex challenge. Furthermore, it is important to note that the findings of this chapter are based on a qualitative approach which produces qualitative results. To quantify these improvements, further studies are required. For such studies, the identified methods and processes need to be tested and measured in practice. Only through this testing a precise value can be determined for the extent to which the geometrical quality can be improved.

Another conclusion from this section is that the methods and process listed in Figure 4.4, should not be viewed as mutually exclusive options. Rather, combining these methods and processes may lead to more optimal improvements of the geometrical quality. Hence, this illustrates even further possibilities to improve the geometrical quality of mega-cast rear floors.

5

Cost Modeling of Geometrical Quality

In this chapter, both a simulation model and a cost model are developed to evaluate the cost of geometrical quality for mega-cast rear floors. The simulation model calculates the cost of scrap and rework using activity-based costing. These two parameters are then used as an input to model the cost of geometrical quality in mega-cast rear floors. To create these models, a literature study is conducted at first, followed by incorporation of expert insight. The models are then developed and applied in several representative example contexts. The methodology is described in Section 5.1, the results are presented in Section 5.2, and the discussion is outlined in Section 5.4.

5.1 Methodology

The purpose of this section is to detail the methodology behind identifying the main cost drivers related to geometrical quality, and developing both a simulation model and a cost model that evaluates the geometrical quality cost for the mega-cast rear floors. The methodology begins with a literature-based exploration of key concepts, including discrete event simulation, activity-based costing, cost of quality, and other relevant terminologies that was deemed necessary in order to understand how to construct the model. To ensure that the models are accurate in comparison to reality, expert insight is gathered from Volvo Cars. Then, the model development is initiated with the utilization of a programming software. Lastly, the models are applied in representative examples to illustrate the cost of geometrical quality in different contexts.

5.1.1 Literature Study

In the process of determining cost drivers related to geometrical quality and building a cost model, a literature study is conducted. The objective of this phase is to gather knowledge about model development, costing techniques, simulation and other relevant concepts. To create models with high accuracy and precision that are comparable to reality, a deep understanding of these topics is essential. Therefore, the literature review prioritizes depth over breadth, focusing on a thorough exploration of the concepts and methodologies deemed most relevant. The process of the literature study is visualized in Figure 5.1.

The process of searching for relevant literature and articles was carried out similarly compared to Section 4.1.1. A range of keyword combinations were utilized by paring keywords, using and/or operators, and using different word inflections. The search was carried out across several relevant databases, including Google Scholar and ScienceDirect. As previously noted, this literature study prioritized depth over breadth; therefore, fewer keywords were used (see Figure 5.1), with greater focus on examining and evaluating the content of the retrieved articles. Furthermore, the search was supplemented by reviewing relevant sources cited within the retrieved articles.

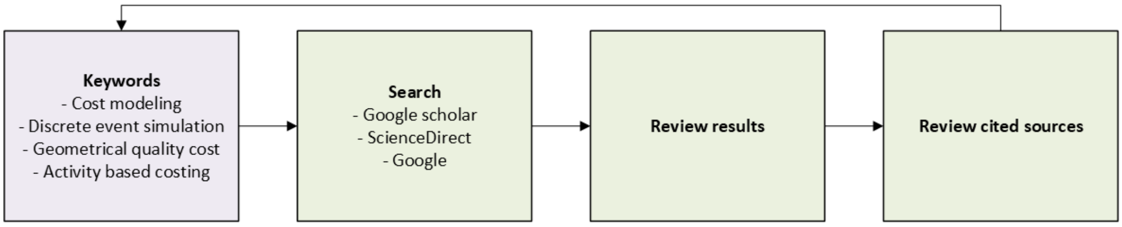


Figure 5.1: Flowchart of literature study process.

5.1.2 Expert Consultation / Interviews

To enhance the accuracy of the model and ensure it reflects a realistic scenario, expert consultations with employees at Volvo Cars are conducted. The objective is to gain in-depth insight into the manufacturing process, thereby aligning the model more closely with real-world perspectives.

As mentioned earlier in Section 4.1.4, three main categories of research interviews were outlined and described; structured, semi-structured, and unstructured interviews. According to [31], semi-structured interviews are guided by a set of predefined questions with the aim to explore key areas of the topic, allowing the respondent to elaborate on their responses. In contrast, unstructured interviews are more flexible, with no structured or well-defined questions and is suitable for situations where there is limited knowledge about the topic [31]. To achieve the objective of gaining in-depth insight into the manufacturing process, expert consultation sessions were conducted using a mix of unstructured and semi-structured interview approaches. Only one or a few questions were prepared, depending on the respondent and the topic. Hence, all interview guides used were structured differently and contained different questions. For illustrative purposes, some sample questions from the different guides are shown in Appendix B. This was deemed an appropriate strategy to ensure flexibility in the interview process while allowing for a deeper exploration of the subject. The sessions also included discussions that helped clarify uncertainties in specific areas, with insights leading to estimates or informed guesses that could contribute to improving the model.

5.1.3 Model Development & Application

Based on the findings of the literature study, a cost model of the geometrical quality in mega-cast rear floors is developed. To further model the scrap and rework cost parameters in the cost model a simulation modeled is developed utilizing activity-based costing to quantify the parameters.

An overview of the methodology used to develop the simulation model can be seen in Figure 5.2. The development of the simulation model began with activity-based costing as a basis in which geometrical quality was integrated as a variable. The process started with creating a high-level visualization, achieved by constructing a flowchart of the relevant manufacturing steps. The flowchart was developed in co-operation with VCC through the conducted interviews. This included the logic and critical aspects in relation to the geometrical quality in the manufacturing process.

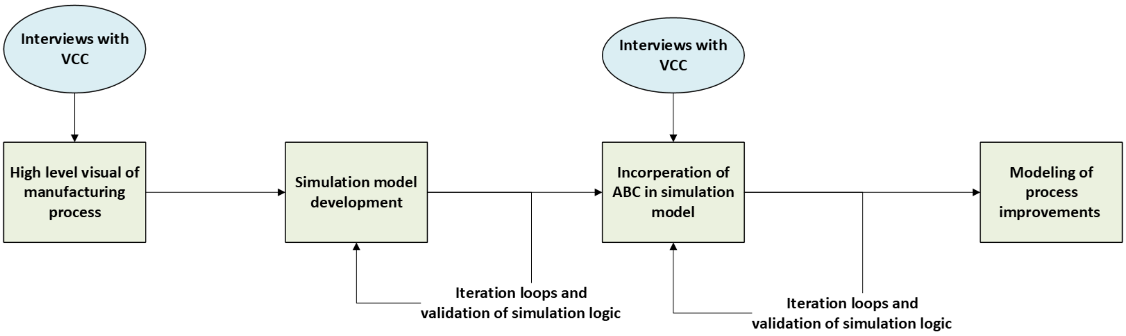


Figure 5.2: Flowchart simulation methodology.

The process was then modeled and simulated in more detail. Several software programs were explored such as Facts Analyzer, Anylogic, Matlab, and Python. Due to availability and knowledge of the programming language, Python was selected. The modeling and simulation of the manufacturing process was iterative, where animation and iteration loops was utilized to verify and validate that the modeled functioned as intended.

The activity-based costing was then incorporated into the simulation model by assigning costs to the different activities in the simulation model. The cost of each activity was either given directly by VCC, or collaboratively estimated through the conducted interviews. This way, the cost of rework and scrap could be simulated and used as an input into the cost model.

Lastly, alternative manufacturing processes were modeled incorporating the process improvements discussed in Chapter 4. From this, the scrap and rework cost could be calculated for the alternative manufacturing processes. By incorporating these results in the cost model, the cost of geometrical quality for mega-cast rear floors could be compared between the different process improvements.

5.2 Results

In this section, the most important findings from the literature are presented along with the fully developed cost model and simulation model. Additionally, the model is applied in three different contexts, and the results of each application are presented in Section 5.3.

5.2.1 Cost Modeling

In this section, the findings from the literature study related to cost modeling are presented as well as the fully developed cost model.

5.2.1.1 Findings From Literature

Activity-Based Costing (ABC) is a costing method that includes allocating costs to different activities such as administrating a customer order, introducing a product variant, starting a production series, and similar [35]. The "activity" term encompasses various levels of scope, ranging from limited and specific tasks, such as container packaging, to broader activities, such as inspection, and extending to entire functions within the company, such as logistics [35]. The choice of activities to include in the method varies between manufacturing, services, and commerce, as well as depending on the specific industry [35].

Further, cost drivers are used to measure the utilization of an activity [35]. A cost driver is what causes an activity to consume resources and is used to distribute an activity's cost to objects or products. Activities and cost drivers must both be decided by the company, as well as the cost of the activity and the volume of the cost driver [35]. This way, the cost (or activity cost) per cost driver unit can be calculated. This makes it possible to calculate how much of the activity cost should be allocated to an object, for example a product or project [35]. Further, it should be noted that one limitation with ABC is that it is dependent on activities being relatively standardized in order to yield meaningful results [35]. Hence, ABC has inherent difficulties in handling complex activities, for example internal activities such as marketing and organizational change [35].

Cost of quality can be divided into two main parts, the cost of conformance and the cost of non-conformance [36]. The cost of conformance is the cost incurred by efforts to improve quality, while the cost of non-conformance is the cost suffered by bad quality [36].

Conformance cost can be further broken down into prevention cost and appraisal cost [36]. Prevention cost is the cost of reducing or preventing defects and appraisal cost it the cost of assessing the quality of the products [36]. Non-conformance cost can also be broken down into internal and external failure cost [36]. Internal failure cost is the cost that are incurred within the manufacturing organization due to failure to conform to specifications, this can be described by the sum of rework and scrap cost [37]. External failure cost is cost arising outside of the manufacturing organization due to failure to conform to specifications. These costs can include warranty claims, loss of goodwill, and lost sales [36]. The entire quality cost hierarchy is visualized below in Figure 5.3. Another view on quality is presented in 2.4.1.1 and illustrated in Figure 2.6, where it is shown that any deviation from the optimal target value is perceived by the customer as a loss of quality. This loss, even if not immediately evident as a failure, can then be captured in a continuous quality loss function.

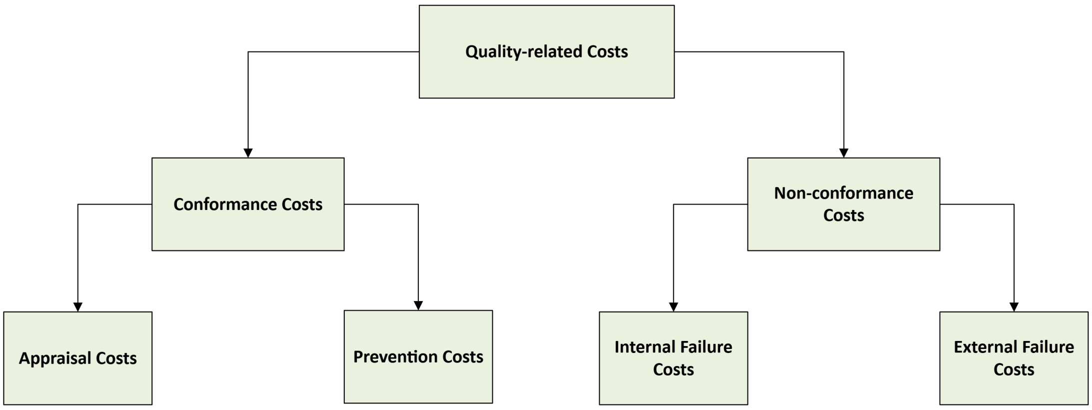


Figure 5.3: Cost of quality, adopted from [36].

5.2.1.2 Model Design

Two main challenges with developing the cost model for the mega-cast rear floors are the complexity and dynamic nature of the manufacturing process. By incorporating the simulation model as a part of the cost model by calculating two of its parameters, the complexity of a real manufacturing process could be captured. This would likely be difficult to accomplish with a tolerance-cost function since such a function is highly dependent on what parameters are assigned to the model. In addition, it might also be difficult to assign such parameters to accurately represent a complex manufacturing line.

A large manufacturing process like this one is also quite dynamic, meaning that changes and improvements are constantly made to the manufacturing process. This also makes it challenging to model and requires the model to be flexible and easily adaptable to change. By incorporating the simulation model into the cost model, it is easy to add and remove activities, gates, etc., which would impact the result of the cost of scrap and the cost of rework. It is also suitable in connecting to process improvements outlined in Chapter 4, which could be adjusted in the simulation model which in return adjusts the outcome of the output parameters of cost of scrap and cost of rework (used as an input in the cost model).

Furthermore, unlike traditional cost-tolerance functions described in Section 2.4.1 and Figure 2.5b, the goal of this model is not to establish a continuous relationship between cost and tolerance or quality. Instead, the aim is to determine the cost of geometrical quality for the mega-cast rear floor in order to evaluate various aspects of the manufacturing process. As such, the model is designed to be applied to specific cases, allowing for the assessment of geometrical quality costs in particular instances.

The cost of quality model shown in Figure 5.3 was applied to assess the cost of geometrical quality in mega-cast rear floors. For cost of conformance the current manufacturing process is used as baseline and would have zero cost of conformance. For the process improvements the cost of conformance was translated into the cost of making changes to the process that improves the geometrical quality, including both appraisal costs and prevention costs. Most of the process improvements relate to prevention cost since their focus is to improve the geometrical quality by reducing geometrical deviation. An example of appraisal costs could for example be if online measurements of every part where implemented. However, for this cost model, the distinction between appraisal costs and prevention costs has no impact and therefore they will be aggregated into a total conformance cost.

The cost of non-conformance will be limited to the internal failure cost since external failure cost is outside the scope of this thesis. Therefore, the non-conformance cost will be modeled by the internal failure cost which can be broken down into cost of scrap and cost of rework. In order to quantify the cost of scrap and cost of rework, a simulation model incorporating activity-based costing is developed and can be seen in Section 5.2.2.

The cost of quality model was used as a basis to create Formula 5.1 showed below. The formula describes the cost of geometrical quality in mega-cast rear floors and is based on the cost to achieve a certain geometrical quality (conformance costs) added with the cost of non-conformance (internal failure cost). The cost of geometrical quality failure is decided by the cost of scrap and rework and, as previously mentioned, will be gained from the simulation model. The cost to achieve a certain geometrical quality is related to process improvement alternatives and depends on both the investment cost and running cost of the improvement method.

$$C_{GQ} = C_C + C_{NC} = C_I + C_{RI} + C_S + C_{RW} \tag{5.1}$$

Where:

$$C_C = C_I + C_{RI} \tag{5.2}$$

$$C_{NC} = C_S + C_{RW} \tag{5.3}$$

All the variables of Formula 5.1 are listed below:

- C_{GQ} - Cost of geometrical quality.
- C_C - Cost of conformance.
- C_{NC} - Cost of non-conformance.
- C_I - Investment cost of geometrical quality improvement.
- C_{RI} - Running cost of geometrical quality improvement.
- C_S - Cost of scrap.
- C_{RW} - Cost of rework.

5.2.2 Simulation Model

In this section, the findings from the literature study related to the development of the simulation model are presented as well as the fully developed simulation model.

5.2.2.1 Findings From Literature

Discrete-event simulation (DES) is a concept within simulation, consisting of two essential building blocks: simulation objects, and events [38]. The simulation objects are a representation of real-world objects, named entities, while the events serve two main purposes: modifying the state of entities, or scheduling future events [38]. With this setup, by utilizing DES, the interaction of entities and their behavior over time can be studied [38]. DES can be carried out by using various specialized simulation software tools.

In [39], it is explained how discrete event simulation can be used for activity based costing (ABC). [39] explains that an ABC model can be developed using a discrete event simulation of the manufacturing process by adding costs to the corresponding activities. [39] highlights that using DES for ABC provides greater flexibility and the ability to greater model complex and dynamic manufacturing systems than traditional approaches. Further, [39] states that simulation based ABC is a powerful tool for measuring and analyzing quality cost. As an example, simulation based ABC can be used for performing an break-even analysis of an additional inspection point in the manufacturing system [39].

5.2.2.2 Process Flow

The baseline configuration of the simulation model is visualized in a flowchart in Figure 5.4. The model consist of multiple process steps (activities), decision gates, buffers, a single starting operation, and several finishing operations. The entities that are being simulated in the model are mega-cast rear floors, with each part being created sequentially. An entity consists of three attributes, corresponding to the three measurement points introduced in Section 3.1.1, i.e. one on the front legs and two on the wheelhouse. These attributes are based on the probability functions gathered from the statistical analysis performed in Section 3.2. In short, every part being created includes three attributes based on three measurements, MPA, MPB, and MPC, each generated from different normal distributions.

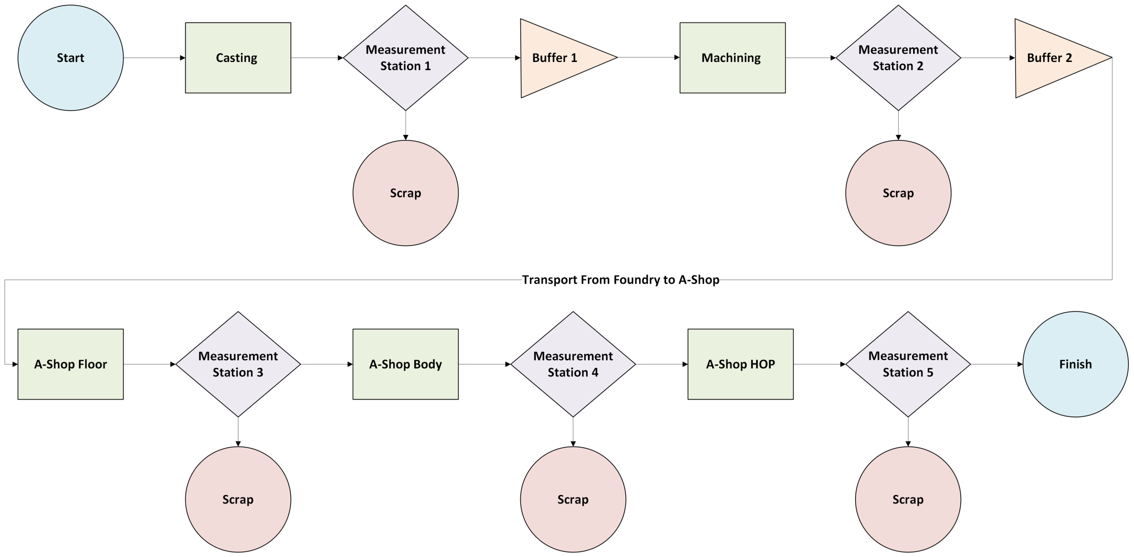


Figure 5.4: Flowchart of simulation model.

Further, the rectangular activities illustrate a process in the manufacturing line, such as casting, or machining. The diamonds represent decision gates, where in this case parts are being measured against the specification limits. This is done by comparing the values of the attributes MPA, MPB, and MPC for the created part, against tolerance limits. If the part is outside the tolerance limits, it is scrapped, otherwise, the part continues to the next step in the manufacturing line. The circular shape represents either the starting or ending point of the flow of a part, which may occur after completing the manufacturing line or being scrapped. A part either finishing the simulation by completing going through the manufacturing line, or being scrapped, also represents two different events in the simulation. An important observation is that there are no rework activities for this particular model. In return, the cost of rework parameter used in the cost model (see 5.1) is equal to zero. However, in such cases where rework activities exist, the simulation model could be adjusted.

The flow of a part begins at the starting point (see the start circle in Figure 5.4), and goes through casting. At the first measurement station, there is a certain frequency rate at which parts are measured. If a part is not being measured, it directly passes through the gate and is stored in the first buffer. Buffer 1 always holds a fixed amount of parts equivalent to the measurement interval. Thereby, when a part measured at the first measurement station is discovered to be outside the tolerance limits, the previous interval of parts (up to the previous taken measurement) are stored in the buffer and are measured as well. If any of these parts are outside the tolerance limits, they are also scrapped. This logic is incorporated in the simulation model to simulate a representation of a realistic quality control process. After the buffer, the part undergoes machining and later into the second measurement station where the same logic as in the first measurement station applies, i.e. parts are being measured at a certain measurement frequency and a fixed amount of parts equivalent to the measurement interval are always being held in the second buffer to be able to check previous parts. The part then leaves the foundry, and is transported into A-shop to undergo different assembly operations. Each assembly operation has one gate in between. Measurement station 3 and 4 follow the same logic, parts are being measured at different measurement frequencies, and if a part is outside the tolerance limits, it is scrapped. If a part is not measured or is within tolerances, the part then undergoes the final assembly in A-shop. Measurement station 5 illustrates another part of the quality control process where the measurement frequency is significantly less than at the other measurement stations. After this gate, the part has finished the simulation run.

Furthermore, activity-based costing is incorporated in the simulation model by adding a cost (or value) at each process (activity) of the manufacturing line. This way, each process, such as casting and machining, has a specific value, which is necessary to determine the scrap cost. The total scrap cost is calculated by adding the cost of the scrapping itself (e.g. handling, logistics, material, etc.) with the value added to the part. The value added to the part is an accumulated value by summing the value added from the previous activities. To exemplify, if a part is scrapped at measurement gate 2, the total scrap cost is the cost of scrapping itself added with the value of machining, as well as casting the part. This way, the total value lost by scrapping a part is captured within the model which can then be used to calculate the total scrap cost and subsequently the cost of geometrical failure, which is an input into Formula 5.1.

5.3 Model Application

Both the cost and simulation models are applied in different scenarios. Firstly, a hypothetical case study is conducted with two different scenarios described in Section 5.3.1. The case study includes examples of numerical values of all possible variables included in the simulation. Therefore, sample values are provided for investment cost, running cost, tolerance limits, distributions of geometrical deviations, scrap costs, rework costs, and measurement rates. It is important to note that that these values are purely illustrative examples and have no relation to Volvo Cars. Thus, the results generated from these values are also not representative of the company. Additionally, the models are applied in three different contexts described in Section 5.3.2, that are of relevance to Volvo Cars. For these contexts, no values are presented and the results of all contexts will be compared with each other.

The simulation model is adjusted accordingly to reflect the specific conditions of each hypothetical scenario and different context. Each simulation model generates the cost of scrap (and rework if necessary) which is then used as an input to the cost model in order to calculate the cost of geometrical quality (see Formula 5.1). In the second and the third contexts, the cost to achieve geometrical quality is also calculated by adding the investment together with the running cost of the improvement method.

To illustrate the results, the cost of geometrical quality based on Formula 5.1 is presented graphically. To further evaluate the different alternatives in relation to each other, the accumulated discounted cost is also calculated. This is based on Formula 2.1 provided in Section 2.4.2. The discount rate is set to 10 %, as it is a commonly used value for financial evaluations [40]. However, since the focus is solely on costs, no data on revenue is included. Therefore, it is more representable to present the results as accumulated discounted costs rather than NPV. The difference is that a higher accumulated discounted cost implies greater incurred costs over time, while a higher NPV entails a higher return on the initial investment relative to its cost. To clarify, the discounted cost of geometrical quality can be seen as a component of the total discounted cashflow. However, in the graphs presented the cost is displayed with positive numbers meaning a higher value equals larger costs. Therefore, a lower accumulated discounted cost corresponds to a higher NPV. Further, both the cost of geometrical quality and the accumulated discounted cost are calculated over a time-period of five years. This period was considered appropriate for evaluating the financial performance of each scenario. A longer time frame would introduce greater uncertainty, making projections less reliable, whereas a shorter period might not adequately capture the long-term potential and implications of each scenario.

Further, for the hypothetical scenarios, examples of numerical values are shown calculated from the inputs stated in Section 5.3.1. For the different contexts described in 5.3.2, the cost of geometrical quality and the NPV of each context are compared graphically without disclosing any numbers. Further, for the hypothetical scenarios, other results are presented in addition to cost of geometrical quality and NPV, to illustrate what the simulation model is able to generate.

For all simulation runs, including both hypothetical scenarios and applications in different contexts, the simulation duration is equivalent to one year of mega-cast rear floor production. There is also a warm-up of 100 parts, meaning that the generation of the results begins after 100 parts have been produced. To ensure statistical reliability, 100 trails are conducted for both the hypothetical scenarios and the applications in different contexts. All reported results represent the average values across the respective trial runs.

5.3.1 Hypothetical Case Study

This section presents a hypothetical case study to illustrate the cost model and simulation framework. The case consists of two scenarios:

- **Scenario A: No Process Improvement** — A baseline scenario in which the casting process results in measurement points that follow a normal distribution with a mean of 0,5 and a standard deviation of 0,75.
- **Scenario B: With Process Improvement** — A scenario where a process improvement is implemented, shifting the distribution mean to 0 while maintaining a standard deviation of 0,75. This improvement involves an investment cost of 150 MSEK and an annual running cost of 2,5 MSEK.

The overall process follows the same structure as outlined in Figure 5.4. However, a hypothetical tolerance limit of +- 2mm has been used of both scenarios. For measurement station 1 and 2, a recheck procedure is implemented: if a measured part is found to be out of tolerance, all parts produced between the last inspected part and the non-conforming part are subsequently remeasured to determine whether they also fall outside the specified tolerances.

The logic for the fist quality check in A-shop (measurement station 3) has also been changed to include rework of the part. Rework is done for each measurement point if the point has a deviation between 2 and 2,5. The rework cost is set to 1000 SEK per measurement point. The rework reduces the deviation to 80% of the original deviation.

The hypothetical scrap and rework cost, as well as quality check intervals used for both scenarios are listed below.

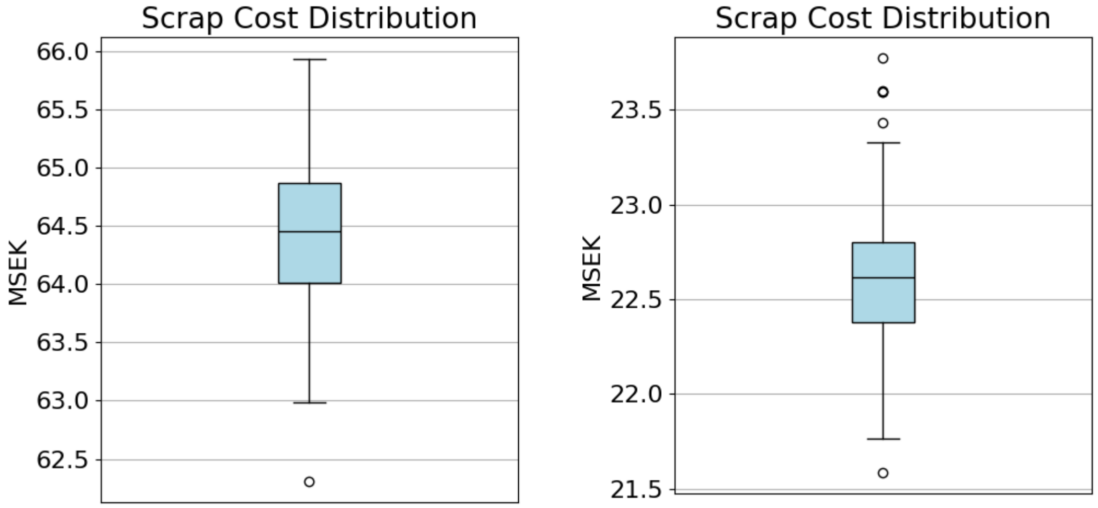
Scrap Cost:

- Measurement station 1: 2,000 SEK
- Measurement station 2: 2,500 SEK
- Measurement station 3: 4,000 SEK
- Measurement station 4: 6,000 SEK
- Measurement station 5: 8,000 SEK
- Scrapped at later stage: 10,000 SEK

Inspection Intervals:

- Measurement station 1: 1 in 10 (with recheck)
- Measurement station 2: 1 in 15 (with recheck)
- Measurement station 3: 1 in 2 (with rework)
- Measurement station 4: 1 in 3
- Measurement station 5: 1 in 10

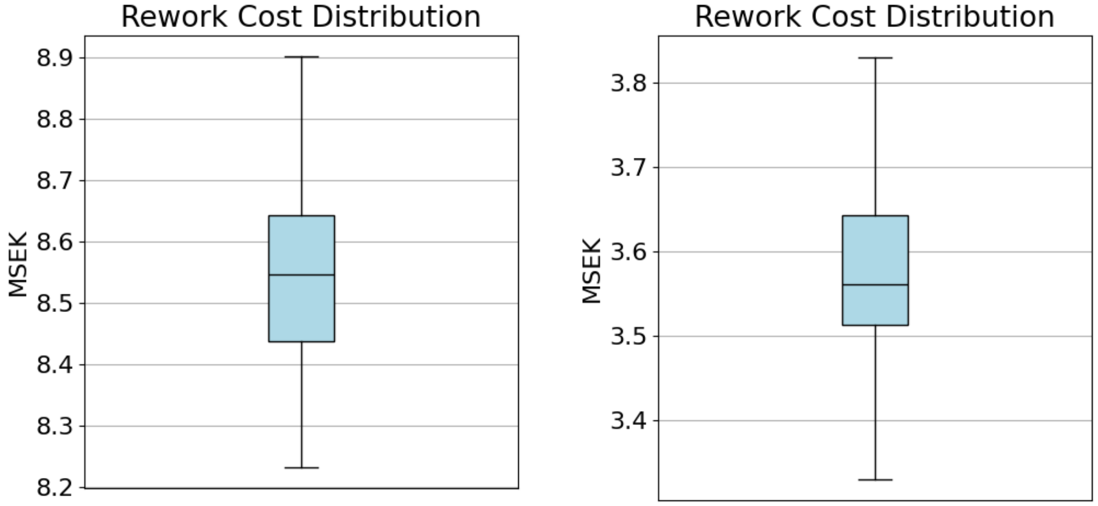
In Figure 5.5 and 5.6 the yearly scrap and rework cost for the scenarios can be seen displayed as box-plots for the trials. It can be noted that, Scenario B has significantly lower yearly scrap and rework cost in comparison with Scenario A. This shows the impact of the process improvement have on the non-conformance part of the geometrical quality cost.



(a) Box-plot of yearly scrap cost for Scenario A.

(b) Box-plot of yearly scrap cost for Scenario B.

Figure 5.5: Box-plot of yearly scrap cost for hypothetical scenarios.

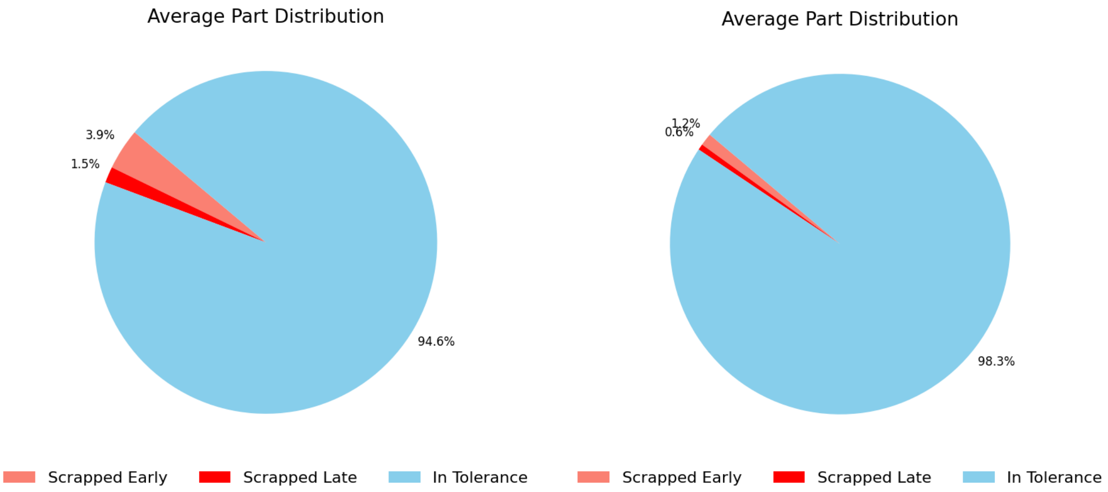


(a) Box-plot of yearly rework cost for Scenario A.

(b) Box-plot of yearly rework cost for Scenario B.

Figure 5.6: Box-plot of yearly rework cost for hypothetical scenarios.

It can be seen in Figure 5.7 that Scenario B has 1,8% scraped parts compared to Scenario A where 5,4% of all parts are scraped where 1,6% are scraped at a later stage (after foundry and A-shop) resulting in significant scrap cost.

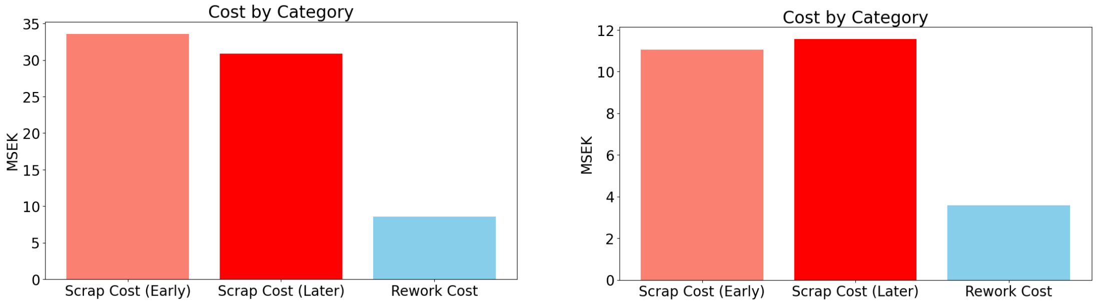


(a) Pie-chart of average distribution of parts in Scenario A.

(b) Pie-chart of average distribution of parts in Scenario B.

Figure 5.7: Pie-chart of average distribution of parts for hypothetical scenarios.

Figure 5.8 illustrates the distribution of scrap and rework costs across the scenarios. A slight difference is observed in the ratio of parts scrapped at later stages. In Scenario B, the cost associated with parts scrapped at later stages is slightly higher than that of parts scrapped earlier. In contrast, Scenario A shows the opposite trend. This difference can be attributed to the recheck procedure implemented during the first two quality checks, which leads to more parts being inspected when the proportion of out-of-tolerance parts is higher. However, since Scenario A produces more parts that fall outside the tolerance limits, the total cost of scrap and rework is significantly higher in this case.



(a) Bar-chart of average cost in Scenario A.

(b) Bar-chart of average cost in Scenario B.

Figure 5.8: Bar-chart of average scrap cost distribution for hypothetical scenarios.

The average rework cost and scrap cost is used in accordance with Formula 5.1 for a five year period and can be seen in Table 5.1 and 5.2 . The cost of geometrical quality is calculated per year starting at year zero where the investment cost is allocated. Cost of non-conformance is calculated as the average rework and scrap cost from the simulation. The cost of conformance is set to zero for the Scenario A to be used as a baseline where the investment and running cost of the improvements are used for Scenario B. It can be noted that Scenario B has significantly lower costs during operation that Scenario A, but a large investment cost.

Year		**0**	**1**	**2**	**3**	**4**	**5**
Cost of non-conformance	Rework cost	0	8,5	8,5	8,5	8,5	8,5
	Scrap cost	0	64,4	64,4	64,4	64,4	64,4
Cost of conformance	Investment cost of improvement	0	0	0	0	0	0
	Running cost of improvement	0	0	0	0	0	0
Cost of geometrical quality		**0**	**72,9**	**72,9**	**72,9**	**72,9**	**72,9**

Table 5.1: Cost breakdown over five years for Scenario A (MSEK).

Year		**0**	**1**	**2**	**3**	**4**	**5**
Cost of non-conformance	Rework cost	0	3,5	3,5	3,5	3,5	3,5
	Scrap cost	0	22,6	22,6	22,6	22,6	22,6
Cost of conformance	Investment cost of improvement	150	0	0	0	0	0
	Running cost of improvement	0	2,5	2,5	2,5	2,5	2,5
Cost of geometrical quality		**150**	**28,6**	**28,6**	**28,6**	**28,6**	**28,6**

Table 5.2: Cost breakdown over five years for Scenario B (MSEK).

The accumulated cost of geometric quality is shown in a graph over five years in Figure 5.9. The two Scenarios can be compared and in absolute terms the cost of geometrical quality is lower for Scenario B for a five year period with a total of 293 MSEK compared to the 365 MSEK for Scenario A.

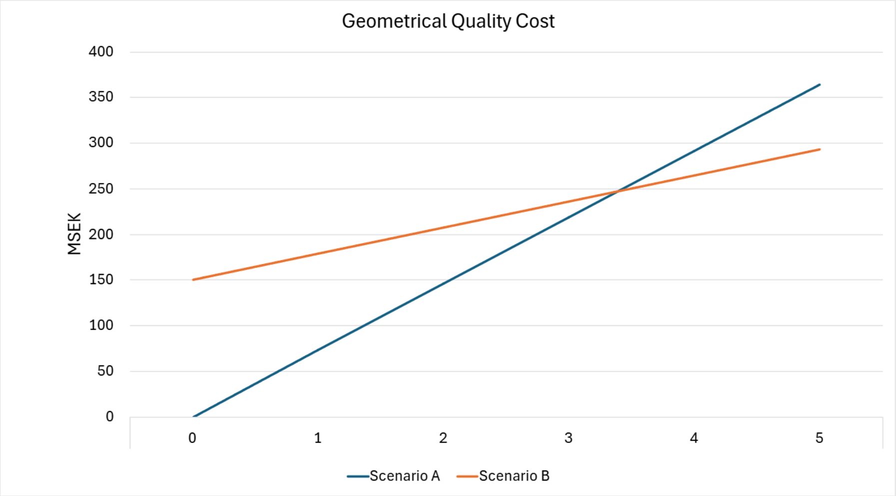


Figure 5.9: Cost of geometrical quality over 5 year period for hypothetical scenarios.

The accumulated cost is also discounted with a 10% discount rate to calculate the discounted cost of geometrical quality, which can be seen in Figure 5.10. It can be noted that for a five year period the two scenarios is closer to each other compared to the absolute cost in Figure 5.9. This is due to the fact that in Scenario B the majority of the cost occur at an earlier point in time than for Scenario A. However, the discounted cost of geometrical quality for Scenario B is lower that that of Scenario A indicating that the NPV of the cashflow will be higher for that scenario with a 10% discount rate.

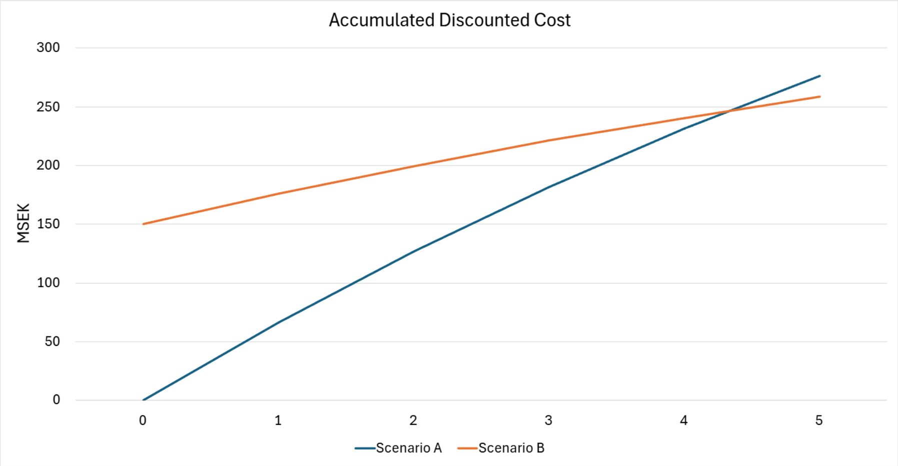


Figure 5.10: Discounted cost of geometrical quality over 5 year period for hypothetical scenarios with 10% discount rate.

5.3.2 Model Application in Different Contexts

The first context represents a simplification of today's manufacturing line (named base scenario) for the car body, where the rear floor is casted in the foundry and assembled together with other parts of the car body in the body shop (A-shop).

The second and the third contexts, like the first, include the current manufacturing line. However, each incorporates a different improvement method to enhance the geometrical quality of the mega-cast rear floors, with the methods derived from Section 4.3.6. In the second context, a fixture during quenching is implemented, and in the third context, an automatic straightening system is implemented. These two improvement methods are selected because they were concluded from Section 4.3.6 to be two of the most promising methods to improve the geometrical quality of mega-cast rear floors. Additionally, all contexts are considered to be the most straightforward to model due to availability of relevant data and other necessary information needed to implement the methods in the simulation model. Therefore, to model the impact of implementing improvement methods, these three contexts were believed to generate the best simulation results in terms of accuracy and reliability.

The results are presented in Figures 5.11-5.14 below. In Figure 5.11, the cost of geometrical quality is presented for the different contexts. It can be noted that the base scenario starts at zero, since there is no initial investment cost. However, over the five-year time period it has the highest accumulated geometrical quality cost, which can be attributed to its steepest slope compared to the other contexts. This is because all costs are incurred from scrap, which represents the highest variable cost among the contexts. In the fixture during quenching context, although there is an initial investment cost, the slope is significantly lower compared to the base scenario, which explains why it becomes a more cost-effective alternative in the long term. The improved cost-efficiency is due to better control over the mean deviation in the front legs, which leads to a lower scrap rate relative to the base scenario. In the automatic straightening context, the investment cost is significantly higher than in the fixture during quenching context. However, the slope is lower compared to the other contexts, which explains why it ultimately becomes the most cost-effective option for the entire time-period. This is because the straightening machines are assumed to maintain produced mega-cast rear floors within tolerance, thereby eliminating scrap. Although the machines incur running costs such as maintenance and electricity, these expenses are lower then the variable costs of the other alternatives, thereby making automatic straightening the most cost-effective option in terms of geometrical quality.

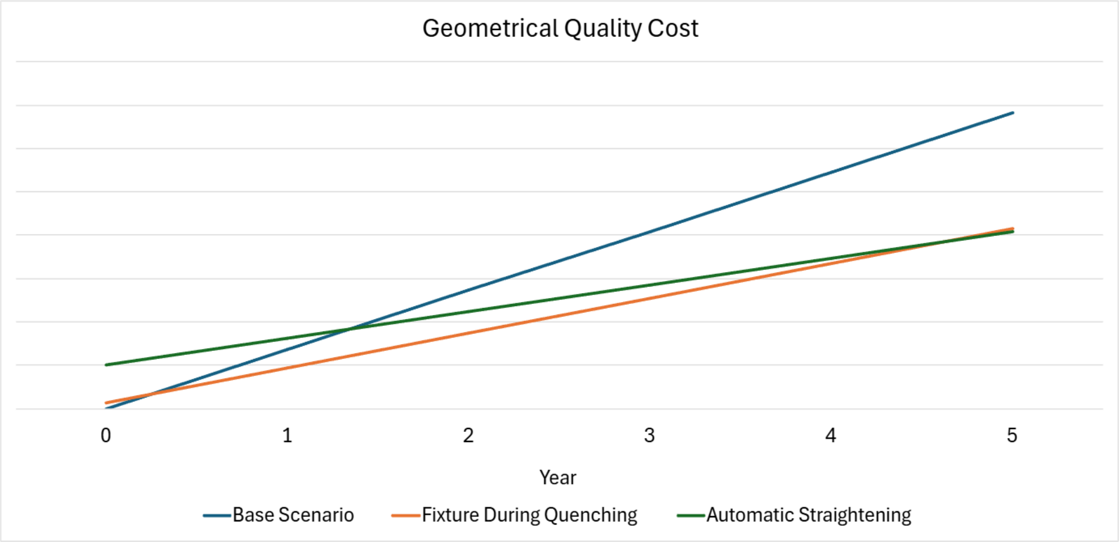


Figure 5.11: Comparison - Cost of geometrical quality.

In Figure 5.12, the accumulated discounted cost of the different alternatives is presented. A similar pattern as in Figure 5.11 is presented, where the base scenario incurs the highest discounted cost over the entire time-period. However, in difference to Figure 5.11, the fixture during quenching context is the most cost-effective alternative, being slightly less than the automatic straightening context. This outcome can be explained by the timing of expenditures, as the automatic straightening context incurs a greater amount of costs early in the period. Due to the 10% discount rate, these early costs have a stronger impact in present value terms, entailing that the fixture during quenching is comparatively more cost-effective over time.

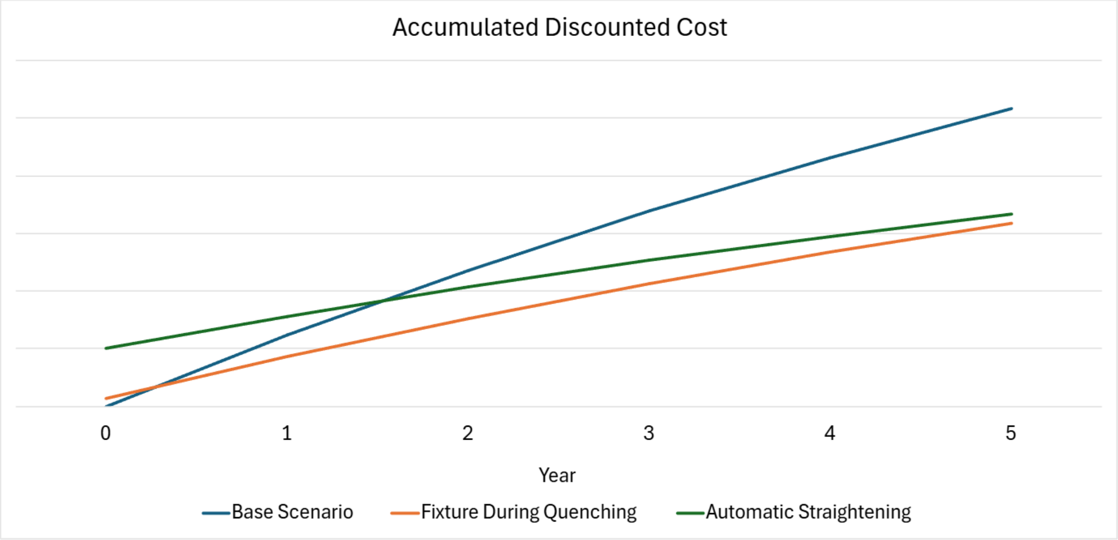


Figure 5.12: Comparison - Accumulated discounted cost.

The total discounted cost of the different contexts over the entire time-period is presented in Figure 5.13, which represents the end point of the curves in Figure 5.12.

An observation is that the fixture during quenching context incurs a discounted cost approximately 40% lower than the base scenario, while the automatic straightening context entails a cost reduction of approximately 35%.

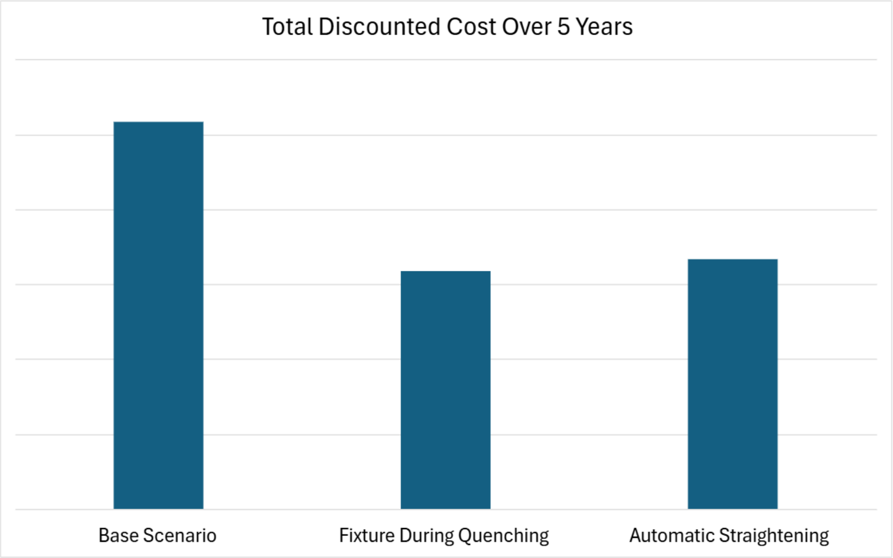


Figure 5.13: Comparison - Total discounted cost.

The average scrap percentage of the different contexts over the five-year time-period is shown below in Figure 5.14. As previously mentioned, the fixture during quenching context presents a significant reduction of the scrap rate (approximately 42%) compared to the base scenario, while in the automatic straightening context the scrap is entirely eliminated.

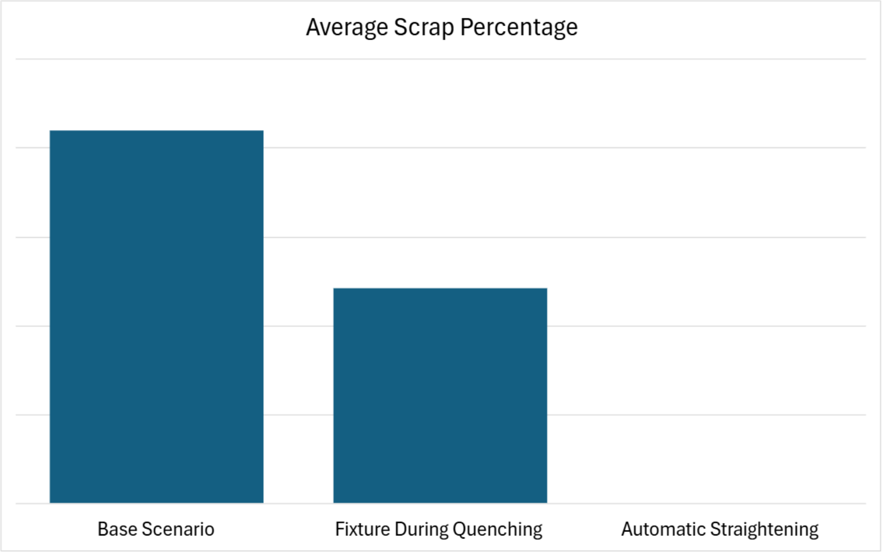


Figure 5.14: Comparison - Average scrap percentage.

5.4 Discussion

In this section, the building blocks and the structure of both the simulation model and the cost model are discussed. Additionally, the input data used in the simulation model is also analyzed. Finally, the results of applying the model in different contexts are reviewed.

5.4.1 Simulation Model

The simulation model is based on a number of assumptions. An example is that the cost of scrapping parts at later stages in the manufacturing line is equivalent to the cost at the last measurement station. This represents a best-case scenario, since in reality the cost of scrapping parts at a later stage would incur significantly higher costs. But since the simulation model is limited to the foundry and A-shop, the cost of scrapping parts at a later stage was not investigated. However, the impact of having a higher scrap cost at later stages would be that the processes with higher scrap percentage (see Figure 5.14) would become more costly in comparison to those that have a lower percentage of scrap. Therefore, it could be argued that increasing the cost of scrap at a later stage could make automatic straightening the most cost-efficient alternative.

Another assumption for the simulation model is that the quality checks operate under the conditions of a stable process. However, in reality, the quality control protocols are more geared towards detecting trends and instability in the process. Measurements taken at the quality controls might indicate certain trends or alarming patterns which could entail more frequent inspections. Thus, in reality, quality checks might be adjusted dynamically in response to observed failure patterns. It is assumed that if the process is stable, the geometrical quality will be satisfactory. Since the quality control procedure is created to detected instability and abnormalities in a process which, when stable, does not produce a lot of parts that are out of tolerances. It is not as effective at detecting and ensuring good geometrical quality in a stable process which produces a lot of parts that are out of tolerance, which is the case in the simulation.

Further, it should be noted that the process flow in Figure 5.4 which is modeled in the simulation, is a simplified version of the manufacturing line for the car body. However, due to the flexibility of the simulation model, it can easily be adjusted. Therefore the model can be used more precisely for the Torslanda plant, and for other plants as well if necessary.

Another assumption in the simulation model is that the manufacturing process is modeled to run continuously. Aspects such as production stoppages or bottlenecks are not accounted for. As a result, the scrap cost does not include factors such as the cost of production downtime or the handling of scrapped parts. If these aspects were considered, the estimated scrap cost would likely increase.

5.4.2 Cost Model

The cost model does not consider all aspects related to geometrical quality costs. For example, external failure costs are excluded. If these were taken into account, the total cost associated with geometrical quality would increase. However, fully incorporating external failure costs may require a continuous model. The current dichotomous approach classifies parts as either conforming or non-conforming, whereas reality is not as black and white. A part that barely meets tolerance limits may still be perceived as lower quality than a "perfect" part by external stakeholders. This perception can lead to external failure costs, even though the part technically conforms to specifications.

The cost model also does not account for other interactions within the manufacturing process. For example, there are many additional quality aspects of a mega-cast part that may impact or interact with its geometrical quality. Parts might be scrapped for reasons such as cracks or porosity in the casting. These defects could potentially correlate with geometrical deviations and thus influence overall costs. It is not completely known, for instance, whether automatic straightening increases internal stress in the mega-cast part (see Section 4.2.5), potentially leading to cracks or other defects. If this is the case, parts may be scrapped for reasons unrelated to geometrical quality, but caused by effort to improve the geometrical quality. However, since the current cost model only considers costs associated with geometrical quality, it does not capture the cost implications of scrapping parts due to other types of defects.

5.4.3 Input Data

Another important consideration is the quality of the input data used in the cost and simulation models. It was discovered that the input data had a significant impact on the simulation results. In particular, the distributions used to model the geometrical quality outcome of the casting had a notably large influence on the final results. To exemplify, a change of the standard deviation or mean of the distribution of a measurement point impacts the scrap percentage and scrap cost significantly. These distributions were based on the findings presented in Chapter 3. However, as previously mentioned, the amount of measurement data available for analysis was limited, which increases the uncertainty of the results. Furthermore, the manufacturing process is undergoing frequent changes, meaning that the input data used for the simulation may not accurately represent the current state of the process.

Additionally, some of the input data used in the cost model is based on estimates. For instance, the discount rate applied is a general rate and does not reflect Volvo Cars' actual cost of capital. Perhaps the most uncertain input based on estimates is the data related to process improvements. Since these improvements have not yet been implemented, both the investment and operating costs were estimated based on internal investigations or supplier quotations, which can be considered reasonably accurate. However, the most challenging aspect of modeling process improvements lies in estimating their effect on geometrical quality. As the improvements have not been tested, there is no quantitative data available to establish distributions for the geometrical quality outcomes. Therefore, these estimates had to be made qualitatively. The necessity of relying on such estimates, combined with their significant impact on the simulation results, introduces a considerable degree of uncertainty into the cost model.

5.4.4 Results

It has been concluded that when applying the model in different contexts, both process improvement alternatives (fixture during quenching and automatic straightening) result in a lower geometrical quality cost over a time period of five years. Ultimately, this is because both alternatives improve the geometrical quality of the mega-cast parts to such an extent that the cost of non-conformance is significantly lower in comparison to the base scenario. This result indicates that both improvement alternatives are more cost-efficient options. In Figure 5.13, it was also shown that both improvement contexts also show lower discounted cost over the time period, which may indicate that these alternatives are promising investment options for the future. However, there are a lot of challenges with the implementation of such improvement alternatives, and costs which are hidden in this illustration. For example, implementing a straightening system requires additional human capital and expertise to successfully implement it in a large scale production. This could include trial runs in a pilot project, calibration of the machines, and similar.

Further, there are assumptions made in relation to the improvement contexts that likely affect the outcome of the result. For the fixture during quenching, this assumes total control for the mean of the front legs, which represents the absolute best case and could be very difficult to succeed with in reality. Therefore, it is likely that the mean of the geometrical deviation in the front legs is more than assumed for this context, which likely would cause a higher scrap rate, and thereby a higher cost of geometrical quality than what is presented. For the automatic straightening context, the machines are assumed to maintain every measurement within tolerance. This also represents an ideal case and might be difficult to succeed with in reality. For example, it is unclear how large a deviation the system can tolerate without introducing any defects. Also, the machines might have a slight deviation themselves, which is not included in the simulation. As mentioned in Chapter 4, there might also be an effect on material properties and it is uncertain what this effect would be. Further, in both improvement contexts, there could be other causes of scrap not modeled in the simulation such as defects, human error, and similar, and it is uncertain how those factors would impact the scrap cost.

The metrics used in the NPV calculations significantly influence the results. The investment timeline was set to five years; however, it is quite possible that the actual timeline extends beyond five years. If that were the case, the context involving automatic straightening would have the lowest discounted cost among the three contexts. As the timeline extends, the difference in discounted costs becomes more pronounced, further favoring the automatic straightening context. Another key metric is the 10% discount rate, which is based on assumptions and does not reflect the actual cost of capital for VCC. Nevertheless, the discount rate does not have as significant an impact on the different contexts. If the discount rate were zero, corresponding to the accumulated cost shown in Figure 5.11, it can be observed that the automatic straightening option has the lowest cost, even after five years.

The results shown from the cost model could be interpreted as fixture during quenching is the best option in regards to the geometrical quality cost. However, it is important to note that the cost model, simulation model and input data includes a lot of assumptions and uncertainty. Therefore, the results of this cost and simulation model should not be used as definitive or as a basis for decision-making. Instead, they should serve as a guide, highlighting the potential impact of geometrical quality on cost.

5.4.5 Conclusion

The aim of this section was to quantify and model the cost of geometrical quality for the mega-cast rear floor. A model of the cost of geometrical quality in mega-cast rear floors was developed and can be seen in Formula 5.1. To establish the internal failure cost a simulation model was developed to quantify cost of scrap and rework. To quantify the cost of geometrical quality the cost and simulation model was applied in three contexts: a baseline representing the current manufacturing process, the fixture during quenching process improvement, and the automatic straightening process improvement. The results of the application of the model show that improvement efforts to increase the geometrical quality could lead to lower costs.

However, the cost and simulation model relies on assumptions and contains uncertainties in the input data. The results from the cost model and simulation should therefore be interpreted as an insight into the importance of geometrical quality and its potential impact on cost in the context of the mega-casting process. In order to use the cost and simulation models effectively for comparing alternative manufacturing configurations, a greater effort must be made to establish accurate and reliable input data, particularly regarding the process improvements. Only then can the results from the cost model and simulation provide reliable insights for decision-making regarding process improvements.

6

Conclusion

In this chapter, the main conclusions from the previous chapters are summarized. Additionally, overall conclusions for the thesis are drawn and recommendations for future work is presented.

In Chapter 3, the aim was to answer the first research question: "How does the geometrical quality outcome differ between rear floor concepts (sheet metal floor, mixed sheet metal/cast floor, and mega-cast floor)?". Statistical tests revealed that significant differences in the means and variances of selected measurement points between some rear floor concepts could be established, while others showed no significant difference. A summary of the results were presented in Table 3.6. However, due to several mentioned limitations, no actual differences in geometrical quality could be established between the platforms. To be able to draw such definitive conclusions, data collection must be done under similar production conditions, and additional data are required.

In Chapter 4, the aim was to answer the second research question: "How and to what extent can the geometrical quality of the mega-cast rear floor be improved?". Methods and processes for improving the geometrical quality of mega-cast rear floors were identified and evaluated. A summary of these methods and processes were presented in Figure 4.5, with the most promising methods highlighted. Further, assessing the extent of geometrical quality improvements is a complex challenge, as each inherently involves a degree of uncertainty. Therefore, improving the accuracy of casting simulations is crucial to more precisely evaluate their impact.

In Chapter 5, the aim was to answer the third research question: "How can the cost of geometrical quality be quantified and modeled for the mega-cast rear floor?". A model for quantifying the cost of geometrical quality for mega-cast rear floors was developed and can be seen in Formula 5.1. Further, a simulation model was developed and applied for quantifying the internal failure cost for geometrical quality. Application of the cost model for different contexts including some of the process improvements from Chapter 4 show that geometrical quality can have significant impact on cost. However, given the assumptions and uncertainties inherent in cost and simulation models, the results should be interpreted as indicative of potential cost impacts, rather than as definitive conclusions.

This thesis has provided valuable insights into assessing the geometrical quality of different rear floor concepts, identified promising methods for geometrical quality improvements, and evaluated the cost of geometrical quality in mega-cast rear floors. However, in many cases, the lack quantity and reliability of data has introduced a high degree of uncertainty into the results making it difficult to draw definitive conclusions. Ultimately, the developed methodology remains applicable for future use and is expected to yield more decisive and actionable results as higher-quality data becomes available.

6.1 Future Work

To accurately compare the geometrical quality of the different rear floor concepts, measurement data must be collected in a consistent manner across all platforms. As much as possible, measurement conditions should be standardized. For example, using the same measurement protocols and equipment can significantly increase the comparability. Additionally, the platforms should be at a similar stage of manufacturing to ensure a comparable level of maturity. A larger quantity of data is also necessary to enable the drawing of definitive conclusions.

Another important consideration for future work is to put further efforts into developing the accuracy and reliability of mega-casting simulations. This is highly important since such results could help assess the impact of process improvements and in return can guide strategic decisions on which improvements to implement.

In order to use the cost model to quantify the cost of different manufacturing configurations, assumption and input data needs to be further refined to more accurately represent VCC's manufacturing process.

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A

Appendix A - Interview Guide 1

1. What is your background?
    - What is your experience within your field?
    - What is your current title and area of expertise?
    - What is your experience with mega-casting?
        - How does this relate to your area of expertise?

2. Can you think of any alternatives or potential solutions to improve the geometrical quality of the mega cast rear floor in series production?
    - Can you explain how the method(s) work?
    - Why do you consider the method(s) to be feasible?
    - What are the challenges with the method(s)?
    - What are the advantages of the method(s)?
    - To what extent can the geometrical quality be improved, i.e. what is the potential of the improvement?
    - How would the method(s) impact cost and cycle time?

3. Among the listed methods, which, if any, are you familiar with/have knowledge of?

4. Which of the listed methods, based on your knowledge, would be feasible for implementation in series production to improve the geometrical quality of the mega-cast rear floor?
    - Why do you consider the method(s) to be feasible?
    - What are the challenges with the method(s)?
    - What are the advantages of the method(s)?
    - To what extent can the geometrical quality be improved, i.e. what is the potential of the improvement?
    - How would the method(s) impact cost and cycle time?

5. Which of the listed methods, based on your knowledge, are not feasible for implementation in series production to improve the geometrical quality of the mega-cast rear floor?
    - Why do you consider the method(s) to be infeasible?
    - What are the challenges with the method(s)?
    - What could be the advantages of the method(s)?

6. Are there any other alternatives or potential solutions to improve the geometrical quality of the mega cast rear floor?
    - Why do you consider the method(s) to be feasible?
    - What are the challenges with the method(s)?
    - What are the advantages of the method(s)?
    - To what extent can the geometrical quality outcome be improved, i.e. what is the potential of the improvement?
    - How would the method(s) impact cost and cycle time?

7. Do you have any recommendations of other people to contact that we can discuss this topic with?

8. Anything you would like to add?

B

Appendix B - Interview Guide 2, Sample Questions

1. For the mega-casting process:
    - What are the stages of the mega-casting process?
    - Where are geometrical deviations discovered?
    - How large do geometrical deviations need to be in order to be considered as scrap?
    - How are measurements taken?
    - What is the cost of scrap at different stages in the mega-casting process?

2. For the body shop process:
    - What are the stages of the process in A-shop?
    - Where are geometrical deviations discovered and how are they handled?
    - Where are measurements taken?
    - How are measurements taken?
    - What is the cost of scrap at different stages in A-shop?

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