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Assessing the impact of quality improvement on production defectiveness: a case study on an automotive manufacturing industry

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ABSTRACT

Overall Equipment Efficiency (OEE) is a crucial performance metric for manufacturing production efficiency. Since the automotive industry is vital to the economy, growing demand from customers and competition has further increased the need for optimised production through an increased OEE. The study evaluates the volume target affected by quality defects, encompassing calculations of First Time Capability (FTC), and assesses the relationship between the implementation of quality control tools and the contribution of quality losses on OEE in the paint shop of automotive manufacturing plants. The study applies a mixed method, evaluating the various production defects at the paint-shop section of the automobile industry and applying both qualitative and quantitative quality tools in identifying nonconformities. The paint quality was assessed using visual inspection and paint thickness measurement in the range of 4–7 mils using the paint thickness gauge and production data using qualitative tools. A correlational research design was adopted using qualitative and quantitative techniques to determine the correlation between the quality output and the knowledge of quality tools by the focus group in charge of producing and inspecting the painting quality output. The results indicated that the paint shop does not meet the volume targets due to quality defects. The study also showed that approximately 78% of the shop-floor workers at the paint shop section were deficient in the significance of OEE and quality tools to productivity. In comparison, the system has a current OEE of 88.7%. The study further identified missing qualitative strategies and non-compliance with relevant ISO-8504 standards.

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1. Introduction

The automotive industry is vital to the South African economy. This sector provides significant economic and employment contributions to the nation (Ambe & Badenhorst-Weiss, 2011). South Africa's automotive manufacturing sector relies on many companies that supply parts, components, and materials. In addition, it encompasses a vast network of dealerships for retail and vehicle maintenance. This industry stands out in South Africa for its extensive reach, contributing to the economy, and generating employment across various sectors. According to NAAMSA (2023), the number of new passenger cars sold in June 2023 will reach 29,795 units, an increase of 251 vehicles, or 0.8%, above the 29,544 new cars delivered in June 2022 (Balcorta, 2023). According to the report, the automotive industry accounts for 4,3% of the GDP [2,4% manufacturing and 1,9% retail], indicating the significance of this sector to the South African economy. The industry has also contributed to value addition through local supplier networks and has encouraged innovation and R&D activities.

Intense competition characterises automotive manufacturing, increasing customer demand, and ever-increasing expectations for high-quality products. Stakeholders expect to function at 100% capacity, 100% of the time, and produce 100% high-quality products in a perfect factory. This has necessitated many manufacturers to seek ways to enhance their production by streamlining their production procedures and increasing overall productivity. In order to remain competitive in their markets, every manufacturing company employs groundbreaking

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concepts and creative ideas to continuously improve their business operations (Ramesh, 2023). One significant factor that can influence productivity in manufacturing is the quality of the products produced, and implementing quality improvement measures can have a substantial impact on overall production. Hence, quality control methods and tools are frequently used to monitor and improve product quality during the manufacturing process. Companies must prioritise quality improvement measures in production performance by embracing the application of quality control tools and ensuring they achieve the target Overall Equipment Effectiveness(OEE).

OEE is a performance indicator that measures the productivity of equipment/activity or improvement strategies in a manufacturing industry (Ng Corrales et al., 2020). It considers the availability of equipment for an operation as a factor of the uptime, the performance of a task and the quality of what is produced in determining the productivity of a manufacturing industry. The quality characteristic of a product is either measured as a variable or attribute depending on whether it can be ascribed a numerical value. Since the quality characteristic of the car paint is an attribute, any quality defects often result in the product being nonconforming and requiring rework, whether total or partial. This directly relates to the performance of car painting as an operation and the quality factor in determining the OEE of a manufacturing outlay. It implies that if the performance of the painting operation is not standardised or the procedures complied with, this would affect the quality of the car painting, which often results in rework. This quality loss affects the First Time Capability (FTC) of the production output, which can be explained as the ability to achieve the production volume target without rework or quality defects. Therefore, as the number of paint quality defects increases, the rework and time spent on it increases, which directly affects the OEE and productivity of the automobile industry.

The main objective of implementing quality control tools is to identify and eliminate errors, reduce waste, and increase production efficiency. Lean techniques, Pareto analysis, statistical process control, and root cause analysis are some of these tools (Uluskan, 2019). These techniques enhance production stems and increase efficiency and quality through proper implementation. Lean techniques, Pareto analysis, statistical process control, and root cause analysis are some of the quality control tools.

A study by Knop (2021) demonstrated the use of quality tools and techniques to reduce surface defects of steel structures for an automobile engine cover. Similarly, the purpose of this study is to assess the significance of the implementation of quality control tools and the contribution of quality losses to the OEE in automotive manufacturing plants. The study first comprehensively appraises the current process capability, FTC, and OEE, considering the volume and quality targets in the paint shop of an automobile industry using both qualitative and quantitative tools and approaches. Secondly, the components of OEE factors (Availability, Performance, and Quality) that require improvement are identified. The third step is to assess the level of awareness, application and knowledge of relevant quality tools and techniques in the quality control practices in the painting section. A survey is conducted to correlate the existing quality output with the knowledge and application of relevant quality tools and techniques in the painting section. The last step is to identify the inadequacy in the application of the quality tools and procedures as a means of developing guidance for process and quality improvement. The outcome would identify any deficiency in the application of quality tools and techniques for improved productivity and OEE in the paint section of the automobile industry. This would allow automotive manufacturers to gain valuable insight into the significance of efforts devoted to resource allocation and focused initiatives on increased productivity and product quality by studying the significance of quality control tools and OEE on production defectiveness. This study therefore underscores the quality factor of OEE for performance improvement at an automotive paint shop, considering a quality attribute characteristic.

2. Background

One of the crucial achievement indicators for car manufacturers is OEE. OEE indicates manufacturing and production equipment efficiency and considers factors such as availability, performance, and quality. Although quality control tools are widely used to enhance product quality and process efficiency, a comprehensive assessment of their influence on OEE and its subsequent effects on production productivity performance is limited. There is a need for a systematic study that assesses the impact of quality improvement through the utilisation of quality control tools on production performance, specifically focusing on the relationship with OEE.

Quality Control has become one of the most significant advancements in quality management system in the early 20th century (Montgomery, 2019). Competition and customer expectations have grown, and businesses have come to understand how to use quality as a competitive advantage (Darmawan & Grenier, 2021). Managing both efficiency and quality as key performance areas in automotive manufacturing is crucial for the success of businesses in the sector. The quality component of OEE is a critical factor for assessing the OEE of equipment in manufacturing processes. It evaluates the proportion of good-quality products produced by the equipment, considering the total number of units produced, including those that may have defects, rejections, or require rework because they do not meet the required quality standards. Zeng et al. (2015) investigated the impact of quality control tools on the manufacturing performance of an automotive component company. The study affirmed that adopting quality control tools, including SPC and Pareto Analysis, led to substantial improvements in product quality, defect reduction, and overall productivity increase, measurable through OEE. Effective losses during business operations can be determined from the components of OEE, as illustrated in Figure 1. These losses fall under one of the three categories under OEE, as highlighted in Figure 1: availability, performance, and quality. Effectiveness losses are the downtime experienced during production caused by technical issues with the machines, machine set-up, manual operation, re-work due to performance error, waiting times, product quality defects etc.

Therefore, implementing a robust quality assurance principle, using quality tools and techniques would directly impact the quality component of the OEE. Improving the quality of the car painting operation would reduce the number of reworks which in turn reduces the waiting time and delay in other preceding operations. Performance error and rework often result in operational bottlenecks which contributes to the effectiveness losses in the business operation. Therefore, this study examines the impact of utilising these quality control tools to enhance the productivity performance of paint shops in the automotive industry.

3. Methodology

The theoretical concept of the 'research onion' serves as the foundation for one method of developing a research methodology that describes the study design (Saunders et al., 2009). It describes the procedures and steps required to perform a rigorous, critical analysis of the subject of interest. Research philosophy, research approaches, strategy, choices, time horizon, processes, and data-gathering methods are the fundamental layers of research onion. The first level, which is research philosophy, provides the fundamental approach to conducting the study, which can either be deductive or inductive research options available at the selection layer of the research onion (Melnikovas, 2018). A similar methodology was adopted by Gupta et al. (2022) on blockchain-secure message exchange systems and Hossain and Sarkar (2021) in establishing an enterprise's profitability considering inclusive growth. Figure 2 shows the layers of the onion method.

Positivism aligns with an objective and empirical approach that aims to gather observable and measurable data to develop and test theories; hence, this study adopts this approach. Positivism strongly emphasises the use of quantitative methods and seeks to uncover the causal relationships between variables. By adopting a positivist research philosophy, this study focuses on collecting empirical data on quality control tools, OEE, and production efficiency in the car manufacturing sector. This research approach evaluates the capability and quality control of the current system. The theoretical framework of the study stems from the quality factor of OEE which affects the overall productivity of the manufacturing company. This factor can be evaluated and improved using different quality techniques and approaches. This research study therefore assumed that there is a relationship between the application of the quality techniques and approaches and the overall quality output, performance, and productivity of the paint section of the automobile industry. Through a careful analysis of relationships, this method will advance the knowledge of the elements affecting the industry's production efficiency and quality. Furthermore, the findings will identify the missing piece in the quality assurance strategies of the sector and possibly reconcile with emerging solutions in the paint shops of the automotive industry.

3.1. Research approach

In the context of this study, deduction is highly suitable, as it enables the creation of testable hypotheses based on accepted ideas and empirical data. By initiating research with established quality improvement principles and theories, specific predictions or expectations regarding the influence of quality control tools on OEE and production defectiveness can

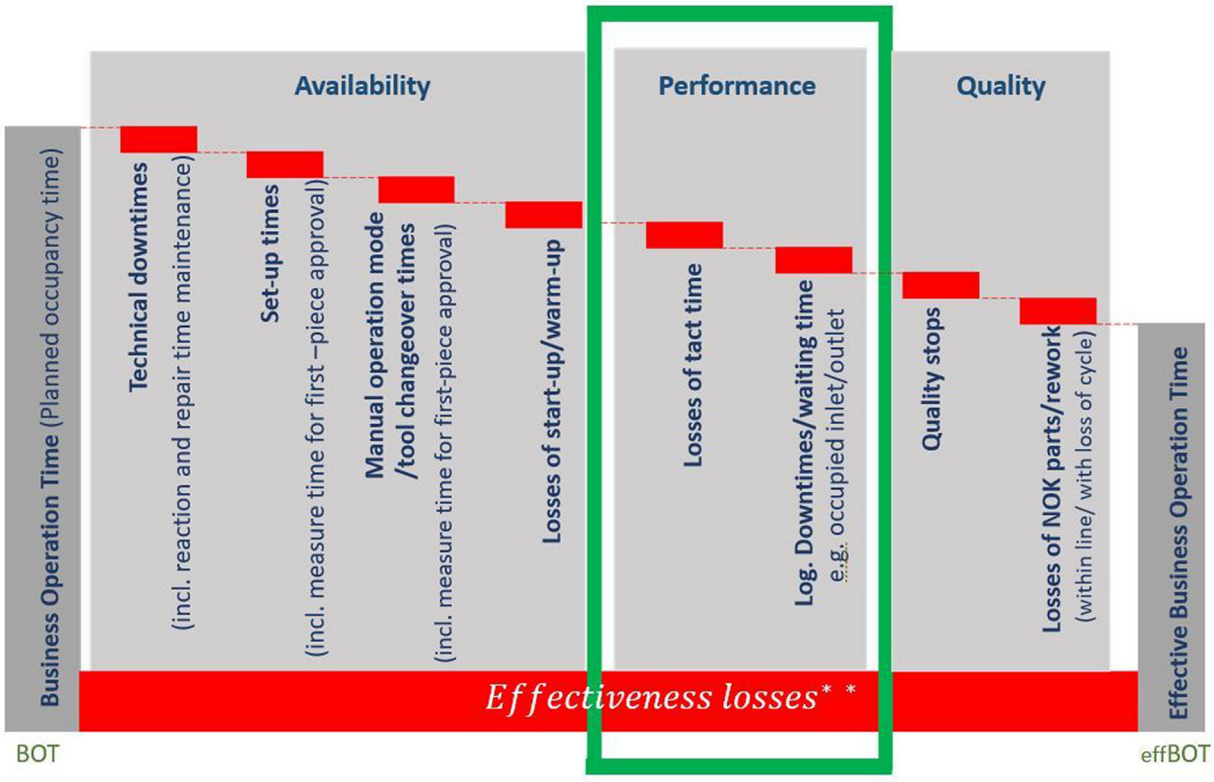


Figure 1. OEE performance factor.

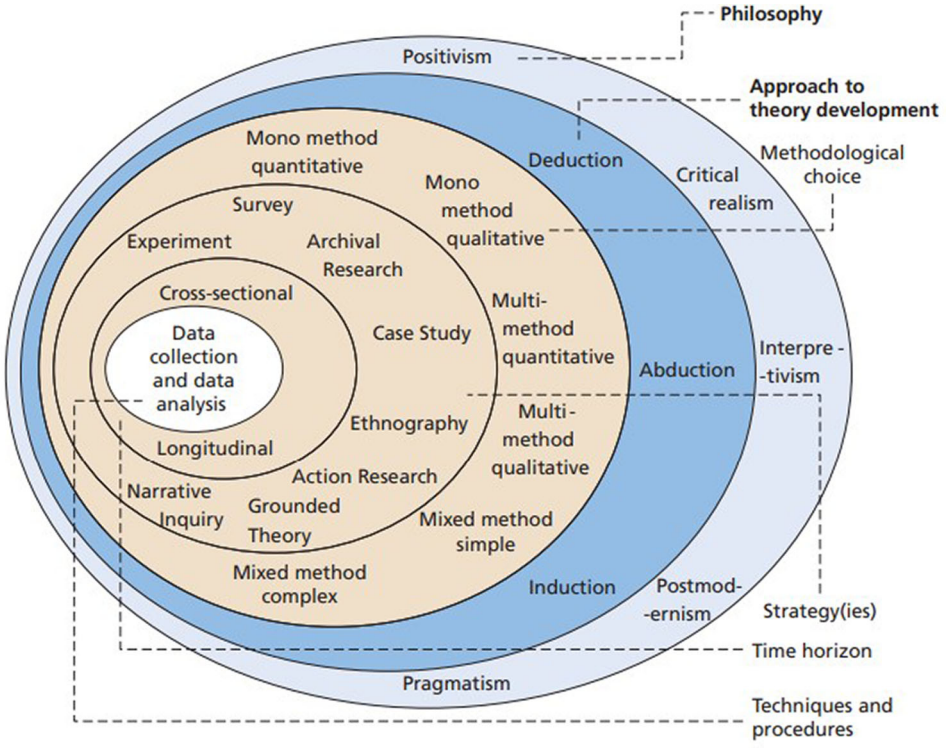


Figure 2. Research onion.

be derived. This deductive reasoning was applied in the study design, gathering of data, and analysis, providing a focused and systematic approach to validate or challenge the formulated hypothesis. Prajogo et al. (2017) adopted a similar approach (deductive reasoning), using quantitative data-

collection methods and statistical models to analyse the fit between supply chain strategies and practices. Martinez-Senra et al. (2015) also applied deductive reasoning based on existing theories and deduced that absorptive capacity is a mediating variable between basic research and product innovation. Therefore, deductive reasoning generates insights from a research study, focusing on unravelling how some antecedents unspool in a given case study and projecting it to a similar scenario (Asif et al., 2021).

3.2. Research strategy

The plan for gathering, analysing, and interpreting data is laid out in the research strategy using a sequential mixed-methods explanation research design suited for this study. The quantitative methodology was accomplished through problem-solving meetings or the analysis of existing internal data sources like the management reporting system (MRS), shop floor management digital system (SFM), and empirical data systems (PLUS), such as production records and quality reports, was employed in the initial phase of the study. To ensure the integrity of the data and reliability, the data is compared to the existing production data and statistical testing is applied to find the average and range of the measured variables in correlation with the obtained data. The checklist datasheet is also referenced to ensure the consistency of data obtained from the MRS and SFM digital systems. Statistical analysis methods, including descriptive statistics and correlation analysis, were used to examine the relationships between the variables and quantify the impact of quality improvement on production productivity.

Implementing an effective OEE performance management routine involves a systematic approach to monitor, analyse, and improve the OEE of a manufacturing process. Systematic production performance evaluation follows a procedural approach, as illustrated in Figure 3.

Volume achievement (production performance) was assessed by collecting data from the manufacturing monitoring system, and the cause-and-effect tool of recurring quality faults was evaluated. Exploring the root cause of quality faults requires selecting the most relevant underpinning quality improvement tools to unravel issues that impact the quality of paint shops in the automotive manufacturing industry. The quality improvement tools that broadly and concisely evaluate root cause analysis are mainly fishbone analysis, Fault Tree Analysis (FTA), Affinity Diagram (AD), Failure Mode and Effect Analysis (FMEA) and Scatter diagram (Stamatis, 2019). An AD, as a quality tool, organises information gathered from brainstorming with more emphasis on sorting than brainstorming, while fishbone analysis identifies the causes of a particular effect, leaning heavily on brainstorming and identifying the causes leading to an effect being investigated. This makes it a preferred quality tool for identifying the root cause of a quality problem. FTA identifies and analyzes the root cause of asset issues before equipment breaks down, whereas FMEA identifies and analyzes the root cause of asset issues after failure or breakdown. While FTA is a deductive, top-down approach to determining the cause of a specific undesired event within a complex system, FMEA is a bottom-up approach. According to Rajapaksha et al. (2015), an FTA is not good at finding all possible initiating faults, whereas FMEA is good at exhaustively cataloguing initiating faults and identifying their local effects. In recent studies, the FMECA tool has been adopted to unravel the root cause of system failure. This quality tool evasively deals with the root cause of a problem in two parts, with the first part being the FMEA while the second part is the Criticality Analysis (CA) that classifies the severity of each potential failure mode based on its severity level (Soltanali & Ramezani, 2023). CA classifies the severity level of the potential failure mode into four (4) bases: catastrophic (causing damage to the system and personnel injuries), critical (causing considerable damage to the system without posing any threat to life), marginal (without damage to the system or threat to life), and insignificant (with no damage to the system and no threat to life or injuries). Because the study focuses on quality defects in the paint shop, the exemption is taken on the likelihood of severity to the system or personnel. Recently, an extended approach has been added to FMEA, which is referred to as new-generation FMEA in the automotive industry. According to Kök and Yıldız (2023), new-generation FMEA furthers the prior scope by integrating risk analysis. This new-generation FMEA can arguably be compared to FMECA in that the depth of analysis is evasive in including all areas of the corresponding impact of the effect being investigated. Because the scatter diagram is a quantitative analytical tool, nonquantitative tools are preferred for investigating and analysing the root cause of quality defects in paint shops in the automotive industry. Therefore, using in-depth FMEA and Fishbone analysis, the root cause of quality faults was evaluated.

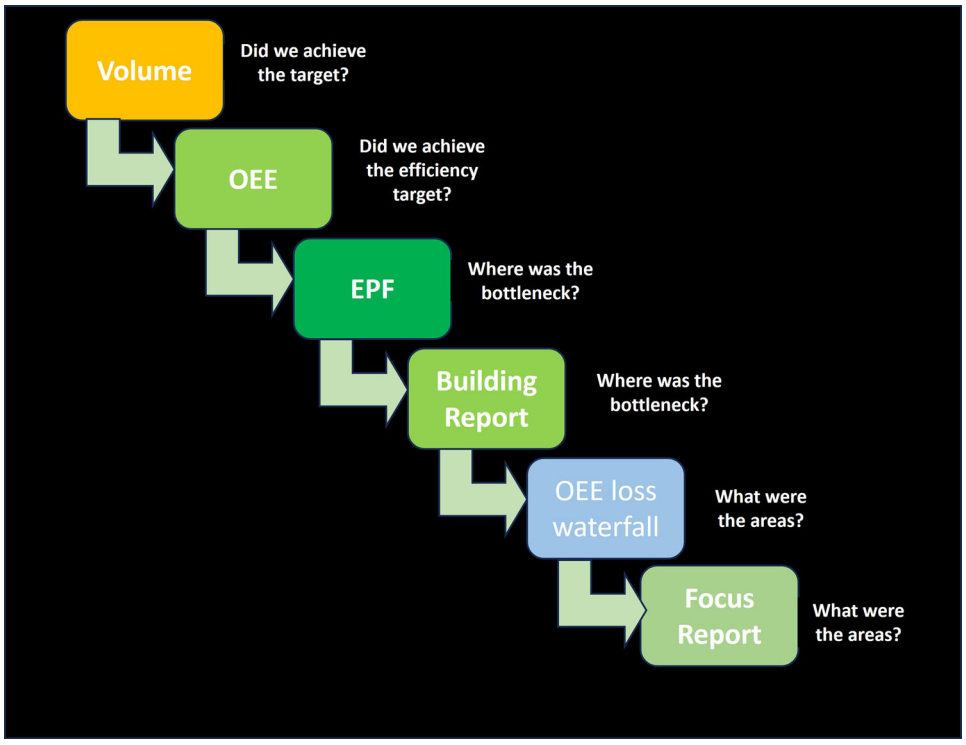


Figure 3. Study overview breakdown.

The volume target is affected by the substandard quality encompassing calculations of first-time capability (FTC) and Jobs Per Hour (JPH). OEE is evaluated using Equation (1) as a function of availability, production efficiency, and quality.

$$\text{OEE} = \text{Availability}^{*}\ \text{Performance}^{*}\ \text{Quality} \quad (1)$$

The third level evaluates the Equipment Performance Factor (EPF) to delineate instances of operational imbalances, specifically, the contrasting dynamics between run-full and run-short conditions resulting from bottlenecks attributable to quality-related factors. This is followed by a comprehensive examination of various quality-related facets that exert discernible impacts on productivity while also considering OEE water loss, aiming to provide a comprehensive understanding of the cascading effects of quality deficiencies on efficiency and productivity during manufacturing processes. The last step investigates receptive faults and meticulously dissects their occurrence and repercussions in the production environment.

The objective of this phase was to quantify the impact of quality improvement on production productivity. Qualitative data were examined to provide contextual insights and narratives that complemented the quantitative findings. The qualitative method adopted for the study is narrative analysis because the intent is to understand the quality challenges, tools and approach based on the experience of the floor workers in the painting section of the production line. The formulation seeks to enhance the understanding of the causes and effects of the quality challenges highlighted by the qualitative approach, as well as the mode of failure of the quality defects. Open-ended questions and probes were asked to the process and operational staff, such as plant managers, quality control personnel, and production line workers, to explore their perspectives, experiences, and related challenges. The qualitative data collected were analysed using qualitative data analysis methods, such as content analysis or narrative analysis with the application of FMEA and Cause-and-Effect tools. To ensure the reliability and validity of the findings, the formulation of the narrative analysis was consistent, focusing on Painting methods, materials, machines, environment and human factors for the cause and effect, while FMEA on trigger processes such as the output, process, trigger, and sensor. Minimising bias is very important when collecting qualitative data, and this was achieved by taking the following steps.

- Random selection of correspondents from the paint shop
- Conducting individual independent interviews.

- Ensuring non-disclosure of identity by correspondents.
- A sample size of 85% of paint shop workers.

The highlighted steps help to minimize bias in the qualitative data by ensuring a comprehensive, unreserved narrative analysis of the processes and procedures in the paint section of the automobile manufacturing industry. Since the paint shop is a section of the whole manufacturing facility, over 85% of the workers in this section, across different shifts, are independently interviewed to get comprehensive and unbiased feedback. This assists in dealing with the limitations of the approach. Merging the findings from qualitative and quantitative approaches provides thorough knowledge of the influence of quality improvement on another factor (Adebanjo et al., 2021; Morton et al., 2018; Singh et al., 2021), which in this study is production productivity. The empirical evidence in this study delineates the challenges of quality management in the paint shop of an automotive industry, either for or against the claim by Bysko et al. (2020) that real-life production is very often not executed according to the assumed MPS based on the occurrence of uncertainty conditions.

4. Result analysis and discussion

The focus of this section is to present a comprehensive analysis of the collected data, unveil the key findings, and engage in a thorough discussion of the results. Quantitative data were collected in the paint shop within the plant, where downtime loss, business operating time (BOT), and effective business operation time (eBOT) data were collected from the equipment performance metrics. Data from the production facilities are captured through the MRS software, which runs on a Plus-Client Human-Machine Interface (HMI) device integrated with programmable logic controllers (PLCs), which are industrial-grade devices for controlling and monitoring machinery. The data is validated by comparing it with the production quality checksheet (paper document) for the paint shop section of the company and the average outgoing quality (AOQ) from the production section. There are two phases of the qualitative data, with the first phase involving the interview of 75% of the Paintshop production workers to find the causes of quality defects based on factors highlighted under the Cause-and-Effect tool and FMEA. Insights into the quality defects and challenges provided by the in-depth qualitative tools would help identify what is lagging in the application of quality tools and techniques and the quality management approaches. The second data collection phase of this research was acquired through administering the questionnaire. Informed consent is taken from each participant and a confirmation of nondisclosure of identity is given to the participants to ensure non-biased opinions and responses. In addition, since the human participants were not the primary focus of the study, ethical clearance was obtained from the human resource (HR) personnel according to the Tri-Council Policy Statement (TCPS) on ethical conduct for research. The questionnaire was distributed to a sample of 25 participants, consisting of individuals from various roles within the paint shop, including management, the quality loop team, and operators. The sample size represents over 85% of the workers within the paint shop section, providing insights into the level of understanding of the importance and application of relevant quality tools and techniques peculiar to paint shop. Therefore, the sample size is representative of the number of workers within the paint shop, and the result can be used to validate the outcome from the qualitative tools analysis.

This questionnaire-based approach served as a valuable complement to the primary data collection methods, enhancing the depth and breadth of our research findings and enriching the overall research process. The critical step undertaken to facilitate the subsequent data analysis process, allowing for the extraction of meaningful insights and conclusions regarding the impact of quality improvement on production productivity performance in the automotive manufacturing industry, was meticulously recorded using some checkpoints, as illustrated in Table 1.

4.1. Production performance: volume impact

Volume impact in production performance determines whether the manufacturing process meets its production volume targets by comparing the actual production output with the planned targets. First-time capability (FTC) refers to the ability of a manufacturing process to produce a planned volume of products or units without any defects or rework during the first production run. The FTC at the Polish line is referred to as white, while car bodies that require repairs offline in the spot repair areas count against the FTC achievement. Similarly, cars sent to the Reject Line to be prepared for repainting also count against FTC achievement. A typical paint shop area is illustrated in Figure 4. The units that support the FTC achievement are those cars that do not

require any offline repairs; hence, they leave the Polish Line and go straight to the wax Booth and then on to the assembly shop. The data for the FTC units in the paint shop department are listed in Table 2, comprising the production data for 2021 and 2022 and the first quarter of 2023.

$$\text{FTC} = \frac{\text{Total Units produced} - \text{No of scrapped units}}{\text{Total no of units produced}} \times 100\% \tag{2}$$

$$\text{FTC} = \frac{20010 - 3482}{20010} \times 100\%$$

$$\text{FTC} = 82.6\%$$

The bar charts in Figure 5 illustrate the percentage of FTC for the years 2021 and 2022 and each month of the first quarter of 2023. The chart shows that April 2023 has the best FTC compared to the months of the same year, with both 2021 and 2022.

The failure to meet the FTC target of 95% underscores the importance of continuous improvements in quality control and production processes. The volume FTC in Figure 5 indicates that the plant performs at a low FTC from the plant deliverable FTC target of 95%. This metric shows that quality defects negatively impact productivity performance.

Further FTC calculations were examined based on the colour attribute of the product for April 2023. Each colour grade and the corresponding FTC based on the colour target and rejected are illustrated in Figure 6.

Figure 6 shows that none of the colours reaches the target FTC, possibly due to common or specific colour faults.

Analysing the system using Failure Mode and Effect Analysis (FMEA) identifies potential failure modes in the production processes and evaluates their potential impacts on defectiveness. The analysis prioritises these failure modes based on severity, occurrence, and

Table 1. Data collection check point.

Production category	Type of process	Checkpoints used
Paint prep area	Manuel station	End of line (2)
Paint application	Full automation	Proxy reading & Q-gate data (4)
White plate	Manuel station	End of line checkpoint (2)
Off-line rework/reject line	Semi-automated	End of line checkpoint (2)



Figure 4. Paint shop application unit.

detection, aiding the development of targeted quality improvement strategies. Appendix presents the FMEA analysis, and Figure 7 presents the Causes and effects.

The statistical frequency of the causes highlighted in the FMEA analysis is presented using a Pareto diagram to rank the cause with the highest frequency to the lowest, as indicated in Figure 8. This shows that machine downtime owing to breakdowns causes the most quality defects and rework in the paint shop for the car manufacturing production line. This provides an overview of the shortfall in meeting the target volume of the paint shop.

Two categories of recurring issues are identified: system faults and product faults. The recurrent product faults include dust, fibre, craters, pinholes, and blisters. FMEA facilitated a systematic assessment of these fault modes, analysing their severity, occurrence, and detectability, as accessed in Appendix, while also analysing and mitigating product faults to drive quality improvements in the paint shop. Identifying the faults in the INQA system underscores the importance of addressing technical deficiencies within the quality control process. The trigger process from the analysis obtained using the FMEA tool is highlighted in Table 3.

Table 2. Production performance.

Year	Jobs per hour (JPH)	Rejected units	FTC units
2021	25	12083	98610
2022	25	11267	95300
Jan	25	5647	17301
Feb	30	6145	16048
Mar	30	6781	18634
Apr	30	3482	16528

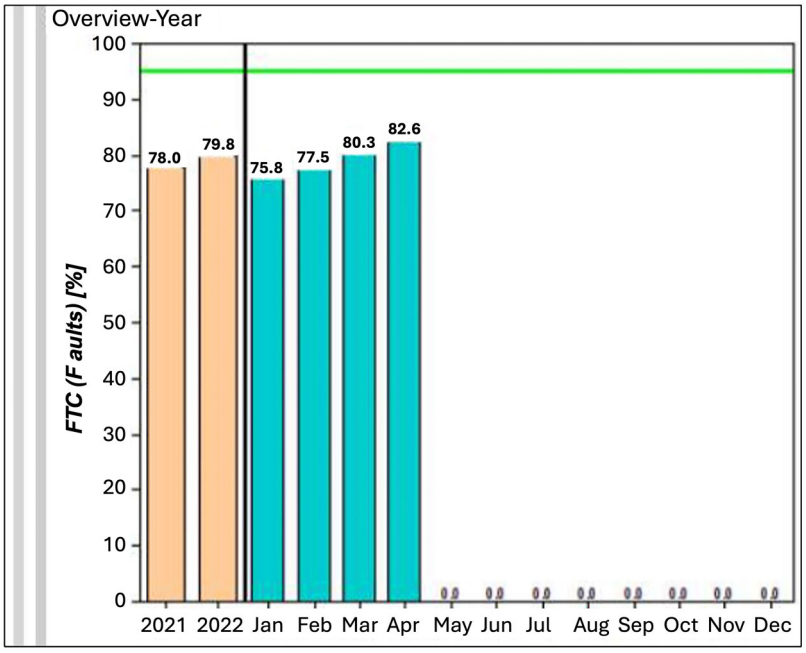


Figure 5. Volume achieved based on FTC.

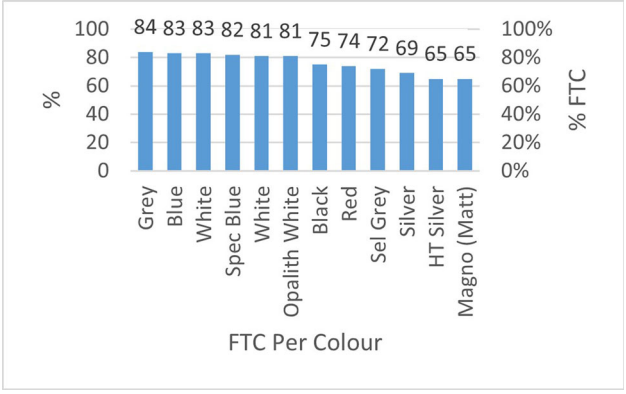


Figure 6. FTC per colour for April.

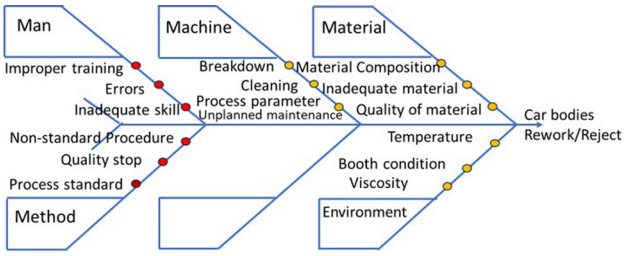


Figure 7. Fishbone analysis of car paint rework/reject.

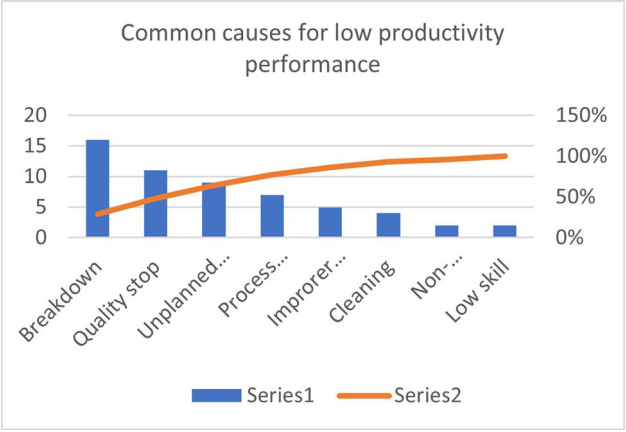


Figure 8. Pareto analysis of the causes of paint rework/reject.

Table 3. FMEA triggered process.

FMEA trigger process				
Responsible	Sensor	Trigger	Process	Output

P/Shop	• New equipment or technology
	• Engineering change
	• Lessons learnt:
	  • External market failures
	  • Internal customer incl. (VoCA/GFP/Shops)
	  • Internal Product Audit
	Quality team within P/Shop
	• Senior manager request
		New process or process change
		Prio 1, Water Leaks/paint delamination (incl. Prio 2)
		Prio 1, Water leaks (incl. Prio 2)
		Prio 1, Repetitive Prio 2 (>3Rep for same PVC seam per week
		Paint faults per week/month
			Risk management
			Process to be followed
				New FEMA
				Review of existing FMEA
				No FMEA or Update is required.

The production schedule was examined to calculate the available time for production to determine the BOT. The data illustrated in Table 4 show the available shifts, durations, and planned stoppages. The available time in minutes and planned downtime can be calculated as follows:

$$\begin{aligned}&\text{Shift 1 (early shift)}\\&\text{Available time} = 490\ \text{min}\\&\text{Planned downtime} = 35\ \text{min}\end{aligned}$$

$$\begin{aligned}&\text{Shift 2}\\&\text{Available time} = 495\\&\text{Planned downtime} = 35\ \text{min}\\&\text{Total shift operation time}: 490 + 495 = 985\\&\text{Total planned downtime (Lunch)}: 35 + 35 = 70\ \text{min}\\&\text{Therefore}: \text{Business operation time (BOT)}: 985 - 70 = 915\end{aligned}$$

$$\begin{aligned}\text{OEE} &= \frac{\text{Good parts} * \text{plannedcycle tie}}{\text{BOT}}\ x\ 100\%\\&= \frac{\text{eBOT}}{\text{BOT}} * 100\%\\&\text{Planned cycle time} = 2.47\text{min/unit}\\&\text{Good parts} = 330\ \text{units}\end{aligned}$$

The BOT provides the available for production but needs to account for unplanned downtimes, such as unexpected equipment failures or stoppages. The eBOT captures the actual productive time by considering planned and unplanned downtimes.

$$\text{OEE} = \frac{330 * 2.47}{915} * 100\%$$

$$\text{OEE} = \frac{812}{915} * 100\%$$
$$\text{OEE} = 88.7\%$$

$$\text{Utilization time factor (UTF)} = \frac{BOT}{\text{Total Time (24hours)}} * 100\% = \frac{915}{1440} * 100\% = 63.5\%$$

$$\text{Total effective equipment productivity (TEEP)} = \frac{\text{Actual Volume} * \text{Cycle time(planned)}}{\text{Total time (24hours)}} * 100\% = \frac{330 \text{ units} * 2.47 \text{ min/unit}}{1440 \text{ min}} * 100\% = \frac{812 \text{ min}}{1440} * 100\% = 56.3\%$$

$$\text{Effective equipment productivity (EEP)} = \frac{\text{Actual Volume} * \text{Cycle time (planned)}}{\text{operating time (shift schedule)}} * 100\% = \frac{330 \text{ units} * 2.47 \text{ min/unit}}{985 \text{ min}} * 100\% = \frac{812}{985} \times 100\% = 82.4\%$$

Table 4. Production schedule.

Shift	Duration of shift (time)	Planned stoppage
Early shift	06H05–14H15	09H30–10H05 lunch
Late shift	14H45–23H00	19H30–20H05

Table 5. OEE per check point.

Production category	OEE
Paint prep. Area	87.2%
Paint application	90%
White plate	75.7%
Off-line rework/reject line	49.9%
Shop (checkpoint 808)	88.7%

Table 5 presents an overview of the OEE for each checkpoint at the paint shop, which shows that while the paint application performed the best, it was still below the OEE target for each point at the paint shop. By comparing the OEE achievement line with the OEE target line and assessing how they relate to the target volume, production management can quickly understand the performance of the manufacturing process, as illustrated in Figure 9.

Because the OEE achievement does not consistently meet or exceed the OEE target, the production volume to the target volume ratio indicates that the process requires improvement strategies. To improve the OEE and production performance, the quality of the process needs to be evaluated. The top five quality issues relating to the paint shop for March 2023 were analysed using the Pareto diagram and are presented in Figure 10.

The fault locations of the top five quality defects were determined using a frequency bar chart, and the results are illustrated in Figure 11. The topmost quality defects, dirt, and dust lead to visible

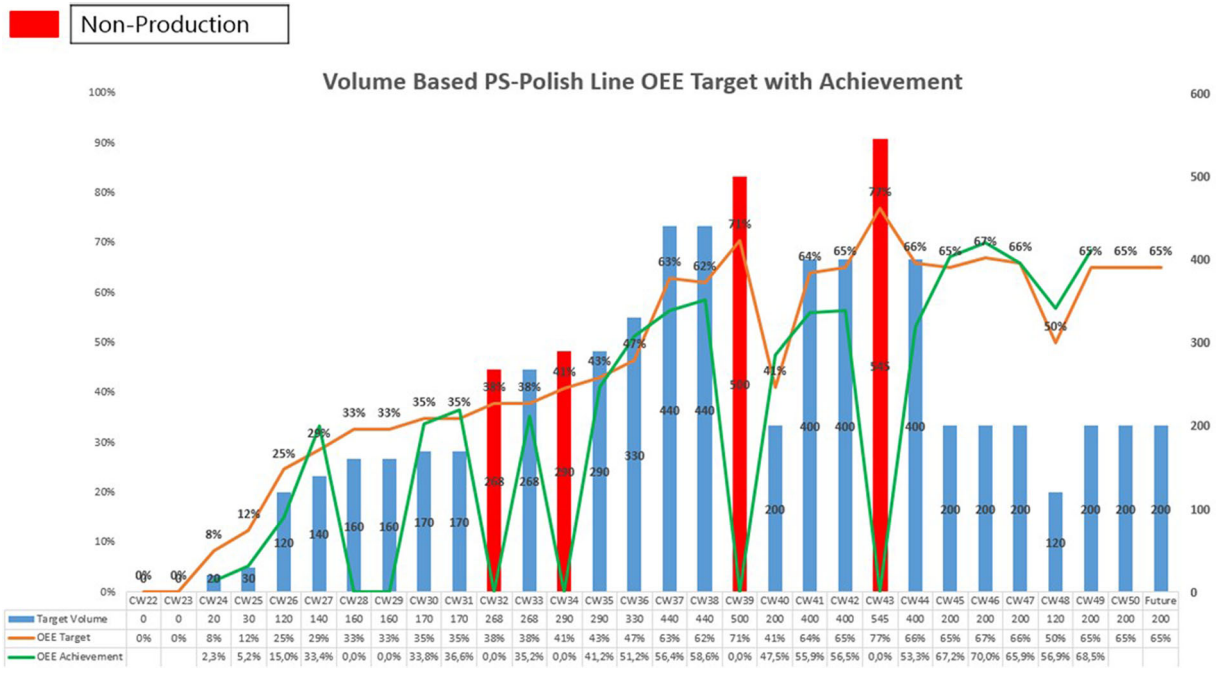


Figure 9. Volume-based OEE target with achievement.

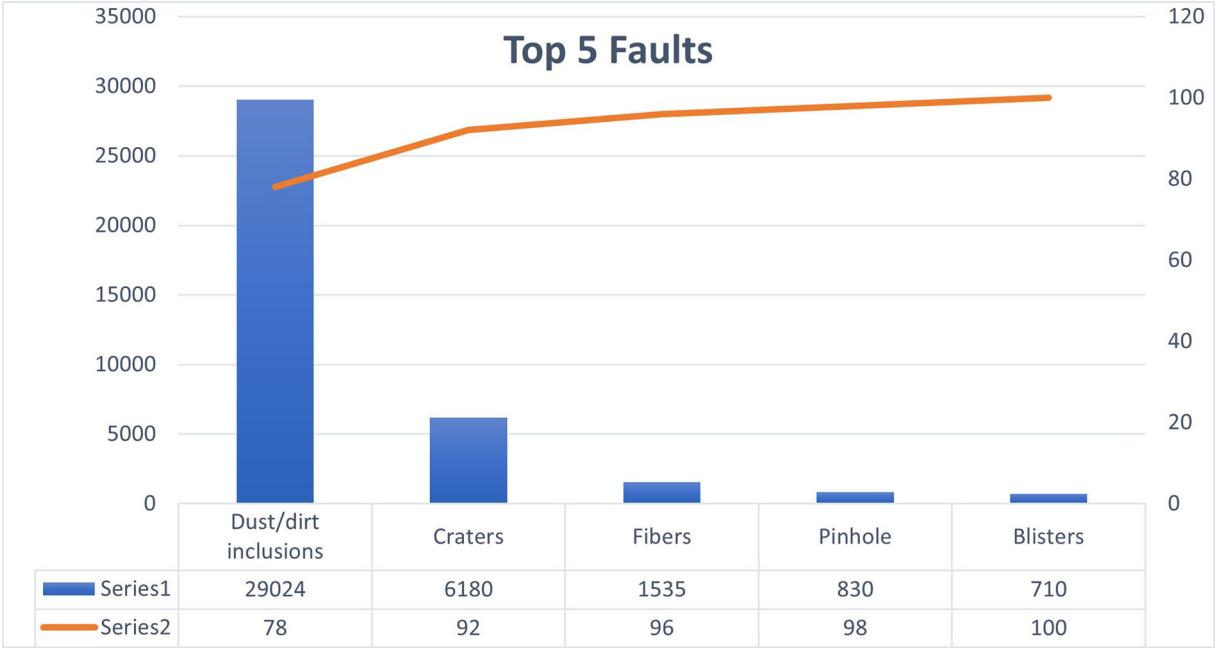


Figure 10. Top 5 quality faults in paint shop.

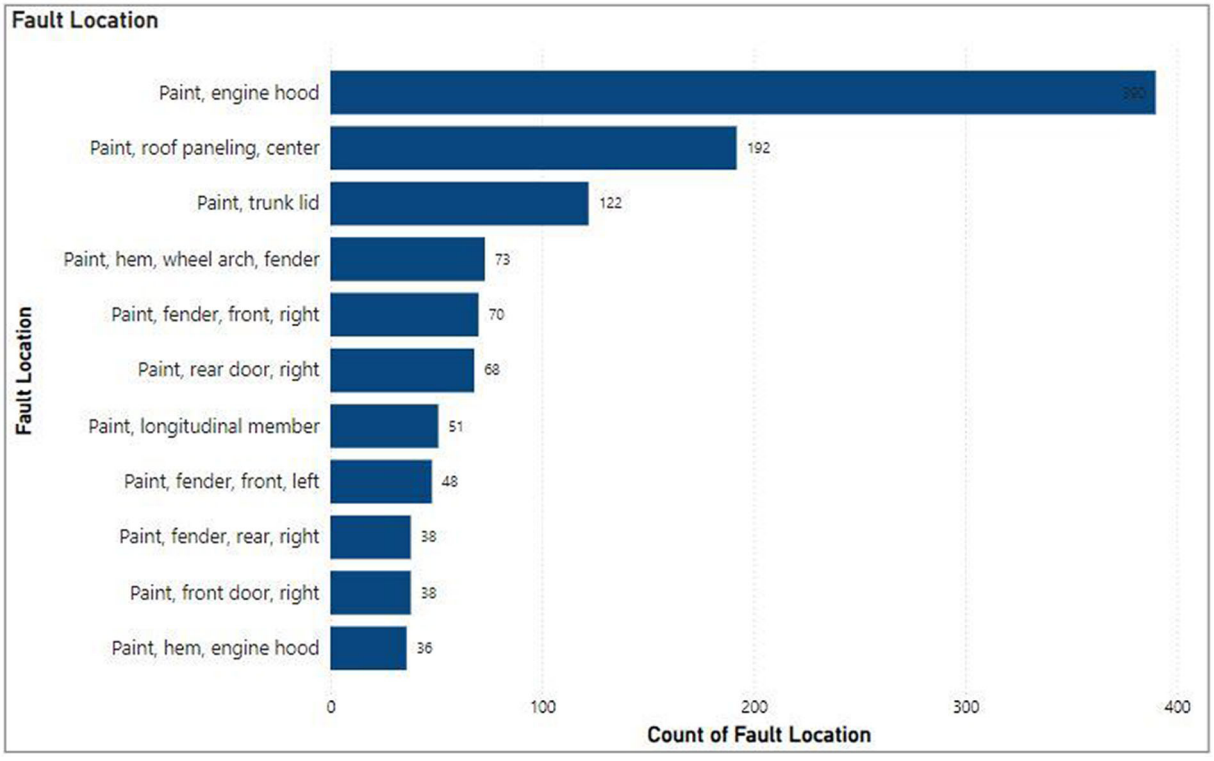


Figure 11. Count of fault location in the paint shop department.

imperfections on the painted product surface, creating an uneven texture that affects the overall appearance of the painted product. Craters are small depressions or dimples that can form on a painted surface caused by contaminants on the surface, improper cleaning, or interactions between the paint and other materials. Similarly, blisters are raised areas or bubbles that can form beneath the paint layer caused by trapped air or moisture, improper curing, or incompatible paint layers. Meanwhile, pinholes are tiny holes that appear on a finished painted surface. Finally, the fibres were embedded in wet paint, causing raised lines or streaks on a painted surface. These quality defects affect the

production volume target and determine the production volume achieved and the OEE.

4.2. Workforce quality tools knowledge evaluation

To evaluate the workforce's (operators, quality team and management) knowledge and engagement with quality control tools, specifically focusing on the production shop floor of the automotive manufacturing industry perspectives, experiences, and understanding of a particular phenomenon, allowing for a rich understanding of the subject matter, questionnaire is administered. The key questions revolved around their familiarity with quality control tools, frequency of usage, training on annotating quality faults using a specific system, confidence in defect identification and annotation, awareness of OEE, and the responses represented through graphs to present a visual summary of the findings.

Six questions were asked, and the results are presented in the charts below with the corresponding questions to allow for the assimilation of each level of knowledge based on the results.

The results from the questionnaire in Figure 12A emphasize the significant need for additional training on OEE and its importance, particularly in the context of the shop floor environment in the automotive manufacturing industry. Figure 12B shows how confident the workers in the paint section feel in identifying and annotating defects, with 5 illustrating the highest confidence level (very confident) and 1 illustrating zero confidence level. Similarly, Figure 12F highlights the perceived assessment of the importance of OEE in quality improvement in the paint shop by the workers, with 5 being the response for 'very important' and 1 illustrating zero importance. The response on training received on annotating quality faults also indicated that 100% of the staff were trained on this, as shown in Figure 12C. However, Figure 12D shows that most of the shop floor workers hardly frequently utilize the quality tools in assessing the quality of their production line which may be traced to their level of familiarity to these tools as Figure 12E indicated that majority were not familiar with the tools. It was evident that most of the shop floor workforce, including operators and the quality loop team, had an inadequate clear understanding of how OEE is measured and how quality defects, rejects, and rework impact it during production. Moreover, regarding the frequency of applying quality control tools, such as Pareto analysis and fishbone diagrams, the results highlighted a potential gap in regular utilization. Many respondents indicated infrequent use of these tools in their daily tasks, underlining the necessity of reinforcing their application and benefits through targeted training programs.

Furthermore, the survey sheds light on the need for enhanced training related to using the INQA/PLUS system to annotate quality faults. A significant proportion of the workforce expressed the need for additional training to improve their proficiency in identifying and annotating vehicle body defects using this system. This signifies a critical area for interventions to enhance the effectiveness and accuracy of the quality control process.

4.3. Operation/process quality evaluation

Bysko et al. (2020) argued that processes in real-life production in the automotive industry are often not executed according to the MPS because of uncertain conditions. Uncertainty in conditions is defined by Meilanitasari and Shin (2021) as any unpredictable event that disturbs the production process in a manufacturing system planned by MRP. These occurrences can create bottlenecks in paintshops, which in turn cause car sequencing problems. Many studies (Leng et al., 2023; Louis et al., 2023; Yilmazlar & Kurz, 2023; Zhang & Ding, 2023) have identified and focused on car sequencing problems in the automobile paint shop industry in recent studies. This has encouraged a lot of research effort in designing the sequencing configuration using different algorithms, while some studies have focused on buffer design as a solution to the problem. This study identified some quality issues in the paint shop, as shown in Figure 10. Designing and modelling an efficient buffer may accommodate the quality challenge in the process by reducing the disruption in the car sequencing process; however, this does not reduce the quality defects or their cost. The heuristic approach used in some of the processes performed at paintshops requires auditing practices using qualitative standards. A similar study by Soltanali et al. (2018) attempts to improve the performance of an automobile manufacturing company (Peugeot and Sports Utility Vehicle (SUV)) by evaluating the OEE of the sections of the production line, including the paint. The results indicate 0.99, 0.70, and 0.38 for availability, performance, and quality, respectively. This shows that quality defects in the automobile paint shop affect the industry's overall performance. In a study by Zulkarnaen et al. (2023), quality defects in the paint shop of an automobile industry in the case study account for 32.6%,

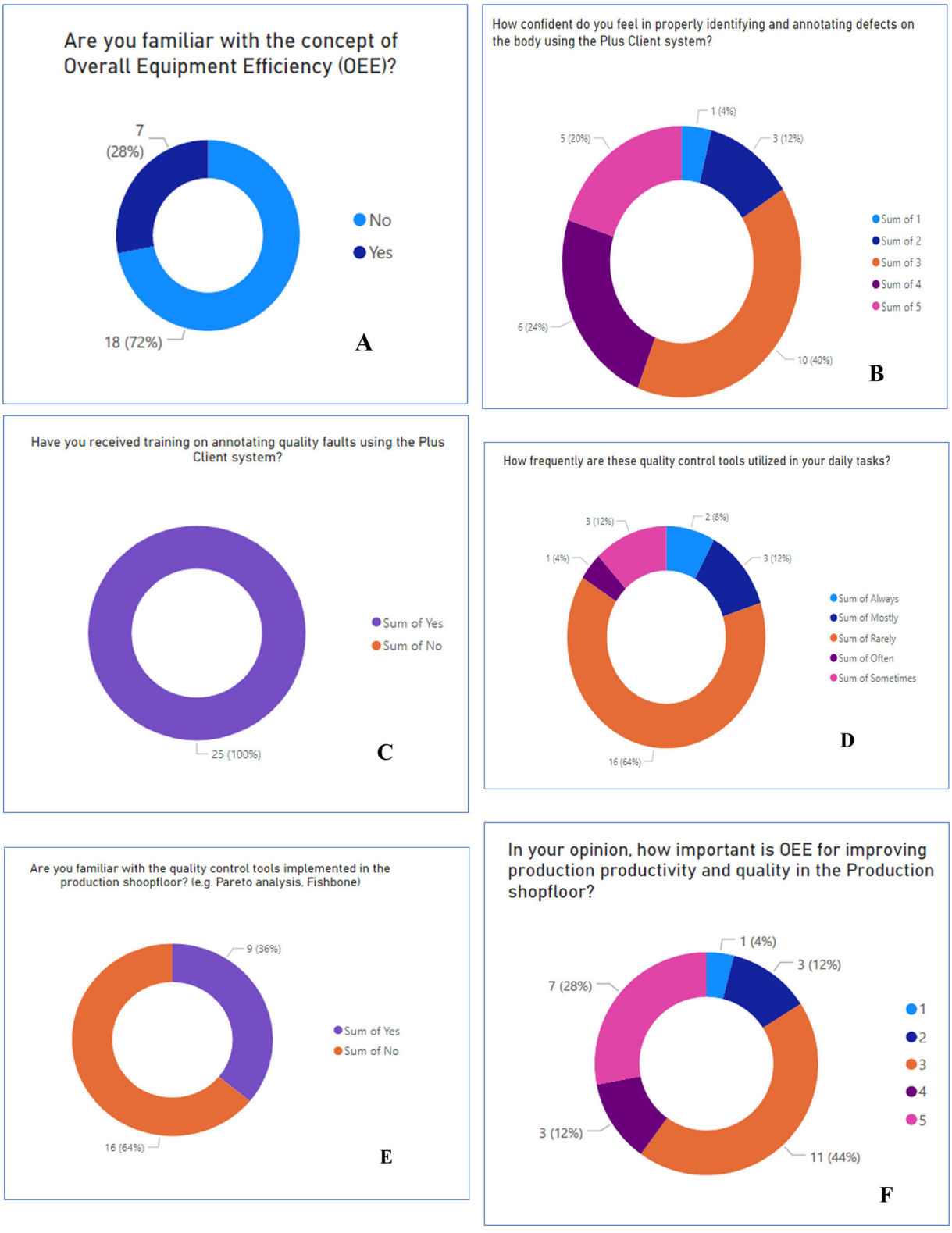


Figure 12. Questionnaire result charts A–F.

which increases operation costs through rework and material costs. DMAIC methodology, with the application of qualitative tools and techniques, was employed to improve the quality output of the paint section. Tamilmaran and Prasath (2022) also applied lean tools to improve the paint shop's OEE, considering similar quality tools such as the Pareto diagram, Value Stream Mapping, and cause and effect for analyzing the root cause of some quality defects.

Table 6. ISO codes and interpretation peculiar to paint shop.

ISO Code	Explanation and interpretation
ISO 8502-5:1998	Preparation of steel substrates before application of paints & related products- Tests for the assessment of surface cleanliness; Part 5: (ion detection tube method) measurement of chloride on steel surface prepared for painting.
ISO 8502-3:2017 reviewed and confirmed in 2022	Part 3: Assessment of dust on steel surfaces prepared for painting (pressure-sensitive tape method)
ISO 8502-4:2017	Part 4: Guidance on estimating the probability of condensation before paint application. It examines whether conditions at the job sites are suitable for painting.
ISO 8502-3:2018 (formerly ISO 8504-3:1993)	Preparation of steel substrates before application of paints & related products- Surface preparation methods Part 3: Hand and power tool cleaning
ISO 4628-1	Paints and Varnishes- Evaluation of degradation of coatings- Designation of quantity and size of defects, and intensity of uniform changes in appearance Part 1: General introduction and designation system.

Critical insight into quality assurance strategies needs to be reviewed to overhaul and address the quality defects and challenges facing the paint shop section. Unlike the assertion that processes are often not executed according to the assumed MPS, owing to uncertainty in conditions, there is a need to implement and adopt some qualitative standards in the production process. A heuristic-based solution that production needs to pay more attention to lies in the design of its quality assurance strategies and the omission of ISO standards and reviews.

Table 6 shows some paint shop standards and procedures for task performance according to ISO standards Kavaliauskas (2018). Highlighting each code of conduct for operation performance addressing the quality challenges at the paint shop section, such as ISO 8502-03:2017 for assessment of dust on steel before painting following the approved methods, and other standards, as mentioned in Table 6, can address these challenges. Strictly following the procedures using a precisely developed SOP with the stated methods on each ISO code standard will reduce the quality challenges and invariably save costs based on quality challenges. This quality management upgrade would imply a revamp of the quality assurance of paint shop operations and output, which would directly increase the productivity of the section.

5. Study limitations and future research

Addressing issues relating to quality defects for quality characteristics that are not measurable is challenging. Evaluating the OEE of the production section of the paint shop entails a deeper understanding of qualitative tools and techniques, together with qualitative and quantitative analysis approaches. The limitation of the study is that the research investigated the paint shop from an automobile industry since the formulation of the study hinged more on qualitative analysis. An in-depth qualitative analysis approach involving narrative analysis and qualitative tools was used for the qualitative data analysis. The subjective experience of each worker may be a limiting factor in generalizing the data across other industries. Even though this challenge was addressed using a sample size of 85% of the workers in the paint section, further studies can be done by extending the research to cover several automobile paint sections to validate the consistency in results.

6. Conclusion

This research study delved into the multifaceted realm of quality improvement within the automotive manufacturing industry, primarily focusing on quality control tools and their implications on production processes, product quality, and OEE. The study identified and analyzed a spectrum of quality tools employed in the paint shop of an automotive manufacturing company and the range of quality defects and quality enhancement strategies. It also suggests that quality improvement initiatives impact the reduction of production defects and augmentation of FTC. The OEE of the paint shop is determined by availability, performance, and quality, and according to Gupta and Vardhan (2016), the quality factor has the most significant impact on OEE. The study showed that production performance can be improved by optimizing OEE with a focus on quality factors due to its complexity in execution and measurement. Similarly, this study establishes that the level of adoption and adherence to quality tools, standards and techniques directly affects the FTC, which relates to the quality component of the OEE. 36% of the paint shop workers are unfamiliar with some quality tools and standards, while 64%

admitted to rarely using the tools daily and consistently, which explained the 82.6% FTC level against the 95% set target. It was evident from the findings that a systematic approach to quality improvement, underpinned by the judicious utilization of quality control tools, can identify and evaluate production defectiveness. It is also noted that applying quality tools in quality improvement strategies will undoubtedly reduce the quality defects in the paint shop process, but without a significant reduction in the quality challenges facing the system, attributing the core gap as an inefficient quality assurance system. The enhancement of FTC emerged as a critical outcome, signifying the effectiveness of such initiatives in ensuring that vehicles meet quality standards immediately after their initial presentation. This implies a need to implement core qualitative standards and procedures for application and auditing processes in the paint shop section of the automobile industry to address the root cause of quality defectiveness.

In addition, the results of the interviews show a positive correlation between the comprehensive quality approach in optimizing the operational efficiency of equipment and machinery in automotive manufacturing and improvements in OEE within the paint shop of an automotive manufacturing company. Therefore, the workforce needs increased knowledge of quality approaches and tools to ensure quality improvement strategies that will improve the overall quality output of the production outlay and, hence, the OEE. More importantly, to address the quality challenges in the production process at the paint shop of the automobile industry, processes and operations must be standardized against quality principles stated by ISO and other relevant standards, such as ASTM, directly instead of in this section of the industry. This would address the quality challenges significantly compared to directing more effort into designing and configuring buffers for car sequencing for the production process. In addition, training workers in experiential and behavioural skills and knowledge would foster a culture of Total Quality Management (TQM) that can improve performance and quality in the automotive manufacturing industry. Furthermore, quality assurance strategies for paint shops and other sectors should be reviewed and audited to implement new and emerging standards for continuous improvement in production. It is therefore suggested that automobile manufacturing companies follow a cycle in the implementation of the proposed quality standards by firstly performing a quality audit and standard evaluation on the production lines, secondly, reviewing the current standard operating procedure (SOP), thirdly, developing and integrating quality standards into the SOP, and lastly updating the quality assurance process and procedures. These steps ensure the quality system and strategies are up-to-date and sustainable over the long term. Integrating these steps, using Industry 4.0 technologies could help with upgrading the production outlay to smart manufacturing Olalere and Olanrewaju (2020).

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Author's contributions

I.O Olalere: Conceptualization, writing of draft and result analysis. K. Ramdass: The review, editing, supervision and revising of the study critically for intellectual content.

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Data availability statement

The data supporting this study's findings are available from the corresponding author, [I.O], upon reasonable request.

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Appendix

FMEA form	System element	Function	Failure	Failure effects	Cause	RPN	S	O	D
Polish Deck to send units to Spot Repair Buffer for rework- Risks should be captured in Polish Deck Risk Analysis	Spot Repair to repair minor paint defects	Correct curing of clear coat application	Yellowing of clear coat after application	Customer expectations of the vehicle are not fulfilled	Reworked areas over-baked	54	3	3	6
Polish Deck to send units to spot Repair Buffer for rework – Risks should be captured in Polish Deck Risk Analysis	Spot Repair to repair small paint defects	Correct curing of clear coat application	Blisters in the clear coat	Customer expectations of the vehicle are not fulfilled	Reworked areas over-baked	54	3	3	6
Polish Deck to send units to spot Repair Buffer for rework – Risks should be captured in Polish Deck Risk Analysis	Spot Repair to repair small paint defects	Correct curing of clear coat application	Delamination of clear coat	Customer expectations of the vehicle are not fulfilled	Reworked areas over-baked	54	3	3	6
Polish Deck to send units to spot Repair Buffer for rework – Risks should be captured in Polish Deck Risk Analysis	Spot Repair to repair small paint defects	Correct curing of clear coat application	Clear coat peeling	Customer expectations of the vehicle are not fulfilled	Reworked areas over-baked	54	3	3	6
Verification and check INQA for defect's location and identification	Verification and check INQA for defect's location and identification	The operator checks faults on INQA to be reworked on the unit	INQA System not working	Customer expectations of the vehicle are not fulfilled	Reworked areas over-baked	15	1	3	5
Verification and check INQA for defect's location and identification	Verification and check INQA for defect's location and identification	The operator checks faults on INQA to be reworked on the unit	Faults not checked In INQA	The ability to assemble is minimally impaired. No or very low functional effect can be identified only by technical personnel.	Operator does not check INQA for faults	45	3	3	5