Jurnal Impresi Indonesia (JII)
p-ISSN: 2828-1284 e-ISSN: 2810-062x
website: https: //rivierapublishing.id/JII/ index.php / jii /index

IMPLEMENTATION OF DMAIC FRAMEWORK TO REDUCE DEFECTS IN SPRAY PAINTING PROCESS

Sarah Ayu Aqila[1], Nur Budi Mulyono[2]
Institut Teknologi Bandung, Indonesia
Email: sarahayuaqilaa@gmail.com[1], nurbudi@sbm-itb.ac.id[2]

Keywords
DMAIC, process capability, production defects, quality improvement, spray painting

Abstract
This research aims to identify the root causes of these defects and propose structured improvements using the Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) methodology. During the Measure phase, data from January to March 2025 indicated that defect rates remained high, with DPMO values of 116,160 ($\sigma = 1.19$), 89,553 ($\sigma = 1.34$), and 110,861 ($\sigma = 1.22$) respectively, highlighting low process capability and the need for urgent improvement. The results show toot cause analysis using Fishbone Diagrams and FMEA identified several key contributors to the high defect rate, including the lack of operator discipline in pretreatment and thickness inspection, inconsistent spraying techniques, suboptimal spray gun performance due to nozzle wear, and dusty spray booth conditions. To address these root causes, the proposed solutions in the Improve phase include implementing a daily pretreatment checklist, structured coating thickness inspections with periodic training and microbreaks, development of a spray painting assistive tool to standardize distance and angle, a preventive maintenance schedule for spray gun components, and the implementation of 5S principles to improve cleanliness in the painting area. The Control phase proposes regular audits, performance documentation, and bi-weekly evaluation meetings to ensure long-term compliance. This research provides practical insights for small-to-medium manufacturing enterprises in Indonesia to initiate structured quality control programs and gradually advance towards higher process capability and reduced defect variability.

INTRODUCTION

Indonesia holds immense potential in the development of the metal stamping, anodizing, and spray painting industries. According to data from the *Badan Pusat Statistik* (2024), the basic metal and metal goods subsector recorded significant growth of 4.14% in 2022, in line with the increasing manufacturing activities in the country. This high potential is evidenced by economic growth and rising demand from various sectors, particularly automotive and electronics. Based on the latest data from *BPS*, the manufacturing industry sector contributed 18.67% to Indonesia's Gross Domestic Product (GDP) in 2023, up from 18.24% in the previous year. The manufacturing industry became the largest contributor to Indonesia's economy in 2023, encompassing subsectors such as electronics and automotive. Data released by *BPS* shows that the total number of motor vehicles in Indonesia reached 148,261,817 units in 2022, demonstrating high demand for motor vehicle and electronics production. This increasing demand further supports the vast potential for the development of these industries.

The metal stamping, anodizing, and spray painting industries play a crucial role in supporting the manufacturing sector in Indonesia. Metal coating is an integral part of contemporary industrial manufacturing. Currently, metal coating is widely used in machinery, equipment, vehicles of all kinds, household appliances, hardware, office equipment, electrical and electronic devices, containers, buildings, clothing, and most manufactured products (Prakash, 2014). Anodizing is an electrochemical process used to form a thick and porous aluminum oxide layer on the metal surface. This process aims to enhance corrosion resistance, hardness, and wear resistance, while also providing a solid base for additional coating or coloring. In the manufacturing industry, anodizing plays a vital role in protecting components from harsh environments, improving aesthetics through various decorative finishing options, and enhancing heat dissipation in products such as heat exchangers or electronic devices (Razzouk et al., 2024). Meanwhile, spray painting is a surface coating process that uses a spray tool to create an even layer of paint. In the manufacturing industry, spray painting plays an essential role in improving aesthetics, protecting components from corrosion, and providing resistance against environmental factors (Gleeson et al., 2022). In a business context, the final quality of each overall process is a crucial element in meeting increasing industrial demands and customer expectations.

As the manufacturing industry in Indonesia continues to grow, there is a shift in customer orientation that increasingly emphasizes product quality, rather than focusing solely on quantity and low prices. This shift pushes companies to maintain and improve production quality to ensure business sustainability amidst an increasingly competitive market. High-quality products not only serve as a key factor in building customer trust and loyalty but also act as an indicator of a company's success in meeting specified standards and requirements (Farchiyah, 2021). Therefore, a strict quality control system at every production stage plays a crucial role, while also presenting new challenges in the development of the manufacturing industry.

The main challenge in the spray painting process at PT Tritek Indonesia lies in the inconsistency of final product quality and the high defect rate, which directly affects production efficiency and customer satisfaction. Several common defects in production include uneven paint thickness, the appearance of bubbles or peeling on the surface, dirt contamination, and scratches on the material. These issues pose challenges to production efficiency, as a high defect rate increases the amount of rework and leads to material waste. In the context of the increasingly competitive manufacturing industry, ensuring product quality meets established standards is critical. Therefore, a systematic, data-driven approach is needed to identify root causes and improve process consistency, thereby minimizing defects and enhancing the company's competitiveness.

Previous research on quality control in the manufacturing sector—especially in spray painting processes—has provided valuable insights into defect reduction and process optimization. For example, Farchiyah (2021) highlighted the shift in customer expectations, emphasizing product quality over quantity and cost, yet did not address systematic approaches for achieving consistent quality in industrial processes. Similarly, Gleeson et al. (2022) focused on spray painting techniques and surface coating improvements but lacked a detailed, data-driven approach to analyze the root causes of defects in production lines. This research fills the gap by applying the Six Sigma DMAIC methodology to systematically identify and resolve defects in the spray painting process at PT Tritek Indonesia. The study provides a detailed analysis of defect causes and process capability, offering practical solutions that can improve quality control and operational efficiency in the spray painting process. By focusing on a data-driven approach, this research offers a robust framework that goes beyond surface-level improvements to address the root causes of defects, which previous studies have not fully explored.

This study aims to explore a quality control system using the Six Sigma DMAIC framework, which is expected to improve the consistency and reliability of production—

particularly in the spray painting process at PT Tritek Indonesia. By focusing on the implementation of a data-driven methodology, this study is expected to contribute to increasing PT Tritek Indonesia's competitiveness in the manufacturing industry at both national and international levels.

This study is driven by specific research questions aimed at understanding the challenges faced in the spray painting process at PT Tritek Indonesia. The primary questions include identifying the key contributing factors to the high defect rate in this process, assessing the current process capability in terms of Defects Per Million Opportunities (DPMO) and sigma level concerning quality targets, and formulating effective solutions to improve product quality while reducing the reject rate in line with established standards. These questions lead to clear research objectives: to analyze the factors responsible for the elevated defect rates, to evaluate the existing process capability in terms of DPMO and sigma levels on the spray painting line at PT Tritek Indonesia, and to develop sustainable improvement recommendations aimed at enhancing product quality and ensuring customer satisfaction. The focus of this research is specifically on quality control methods utilized within the production process at PT Tritek Indonesia, with an emphasis on the spray painting line. The analysis aims to identify the main causes of defects and propose improvements to the quality control system based on data collected from production reports during the period of January to March 2025. However, the research is not without limitations. It solely encompasses activities within the Quality Assurance (QA), Quality Control (QC), and Production departments, focusing primarily on the spray painting line as the key area for quality enhancement. Consequently, the findings are most relevant to PT Tritek Indonesia and may not be fully applicable to other similar companies due to contextual differences. Additionally, the study's scope is confined to the designated timeframe, which may prevent insights into long-term production trends or external factors that could influence quality control processes.

METHOD

Research design serves as a comprehensive framework that guides the research process, ensuring that all components are interconnected and aligned. It is crucial for producing accurate, unbiased, and representative results—often likened to the "glue" that unifies various aspects of a study. This design encompasses essential elements such as participant selection, variable organization, and methods of data collection and analysis. Additionally, it outlines strategies to mitigate the influence of external factors that may distort results, underscoring the importance of a carefully constructed design for the reliability and validity of research conclusions (Dannels, 2018).

In this study, a case study approach is utilized, specifically adopting the Six Sigma *DMAIC* framework—*Define, Measure, Analyze, Improve, Control*—to investigate and enhance the quality of the spray painting process at PT Tritek Indonesia, with the primary goal of reducing the incidence of defective products through a structured five-phase methodology. The *Define* phase focuses on articulating the problem and delineating the process scope, employing tools such as *SIPOC* diagrams and process maps to visualize workflows. Following this, the *Measure* phase involves collecting and analyzing actual quality data using *Pareto* charts, *p-charts*, and capability analyses, thereby establishing a baseline for process performance.

The *Analyze* phase seeks to uncover root causes of defects using fishbone diagrams and *Failure Mode and Effect Analysis (FMEA)*, facilitating the evaluation of risks associated with each cause. Building on these insights, the *Improve* phase is dedicated to developing and selecting effective solutions, while the *Control* phase ensures that improvements are sustained over time through the implementation of the *PDCA* (*Plan-Do-Check-Act*) approach.

Data for this research consist of primary sources, including employee interviews, observations, and internal production output data collected over three months. Employee interviews were conducted with key personnel involved in the production process, providing valuable insights into the main types of defects and challenges encountered. Observations supplemented these interviews by monitoring the spray painting line and analyzing daily check-sheets used for documenting defects, allowing for the identification of recurring patterns and areas needing improvement. Internal data from the *Quality Control* team, including production output reports and defect rates, further enriched the analysis.

The research adheres to the *DMAIC* framework, systematically identifying and addressing defects through a structured approach. The *Define* phase emphasizes problem identification and project scoping, while the *Measure* phase assesses current performance using tools like *p-charts* and *Pareto* charts to highlight significant defect types. The *Analyze* phase focuses on identifying root causes through the fishbone diagram and *FMEA*, prioritizing issues based on severity and occurrence scores. In the *Improve* phase, solutions are developed to address the root causes identified, and the *Control* phase ensures the sustainability of these improvements through documentation, standardization, and ongoing management monitoring.

This holistic approach ultimately aims to enhance the quality of the spray painting process and significantly reduce defect rates.

RESULTS

Define Phase

The Define phase serves as the foundational stage within the Six Sigma approach using the DMAIC framework. Its primary function is to identify the core problem and gain a comprehensive understanding of the process under analysis. In this phase, an in-depth examination of the spray painting process at PT Tritek Indonesia was conducted through field observation, discussions with production management, and a review of documents related to quality reports and production output data. The main focus of this phase is to formulate a clear problem statement, identify the dominant types of defects, and map the entire work process to determine critical points that may potentially cause product defects. The information obtained in this stage serves as the basis for the subsequent phases in the effort to improve quality and control the production process.

Measure Phase

The Measure phase is the second stage in the DMAIC framework. This phase serves to measure the actual condition of the process. In this phase, quantitative data are collected and analyzed to assess production stability, variations, and the performance level of the process. The main focus of this phase is to establish the process baseline based on historical data, identify the proportion and dominant types of defects, and evaluate the process capability in meeting the specified requirements (Jacob and Chase, 2023). Several statistical tools are used in this phase, including the Pareto chart, p-chart in Statistical Process Control (SPC), and process capability measurements (DPMO and Sigma Level). These statistical tools aim to provide an objective overview of process performance prior to the implementation of improvement interventions.

Measurement system analysis (MSA) is used to ensure that data is generated from a reliable measurement system before further analysis. This system helps distinguish whether variations in data come from the process or the measurement itself (Pyzdek and Keller, 2018). Several MSA components applied in the inspection of production results at PT Tritek Indonesia include:

1. Repeatability

Inspections are carried out repeatedly by the same operator using standardized tools and procedures to ensure consistency in both visual inspection and paint thickness measurement by an individual.

2. Reproducibility
   Inspections are performed by multiple QC personnel using the same SOP to ensure consistency is maintained across different inspectors.
3. Bias
   The paint thickness measuring instruments are regularly calibrated to minimize measurement deviation.

Based on data collected during the Measure Phase, the overall defect rates in the spray painting process at PT Tritek Indonesia were recorded at 12% in January, 9% in February, and 11% in March 2025, all of which exceeded the company's internal defect rate target of 10%. A Pareto analysis identified five dominant defect types that contributed to 95% of the total defects, with NG Total (41%), Under Paint (17%), and Paint Bubbles (15%) as the top three contributors. These findings confirmed the existence of a few critical issues causing the majority of quality problems.

Further assessment using Statistical Process Control (SPC) through p-chart revealed the presence of several points beyond control limits, particularly in early January and mid-February, indicating instability in the process due to special causes of variation. Finally, process capability analysis showed that the process had not yet reached a stable or capable state. The calculated Defects Per Million Opportunities (DPMO) were 116,160 in January ($\sigma = 1.19$), 89,553 in February ($\sigma = 1.34$), and 110,861 in March ($\sigma = 1.22$). These sigma levels indicate low process capability, far from the Six Sigma standard and internal target, and highlight the urgent need for improvement interventions.

Analyze Phase

The main focus in the Analyze phase is to identify the root causes of the quality issues found in the spray painting line of PT Tritek Indonesia. After performance measurement was conducted in the Measure phase, it was found that the defect rate was still above the established quality target. Therefore, in this phase, an in-depth analysis will be carried out to explore the factors that contribute to the high defect rate. The methods used in this phase include a fishbone diagram to systematically identify possible causes based on main categories, as well as Failure Mode and Effect Analysis (FMEA) to evaluate the risk level of each potential defect cause. With this approach, it is expected that the most critical root causes can be prioritized and addressed effectively in the Improve phase.

Based on the analysis results of the Pareto Chart, it is known that the types of defects with the largest contribution to total defects are:

a. NG Total with 41%,
b. Under Paint with 17%.

These two defect types cumulatively account for 58% of the total number of defective products in the spray painting process at PT Tritek Indonesia. Therefore, the root cause analysis will be focused specifically on these two types of defects. This focus selection aligns with the Pareto principle (80/20 rule), that most of the impact can be addressed by fixing a small number of main causes. NG total is an aggregate category that includes various major, unrecoverable defect types, so in this analysis, there is a possibility of overlapping causes with specific defects such as under paint.

a. **Root Cause Analysis**

This diagram groups various possible causes into five main categories, namely Man, Method, Machine, Material, and Environment. This classification aims to identify the contribution of these factors in a structured manner to support the determination of more effective improvement priorities in the next stage. The following shows the result of the root cause analysis of the NG total defect in the form of a fishbone diagram.

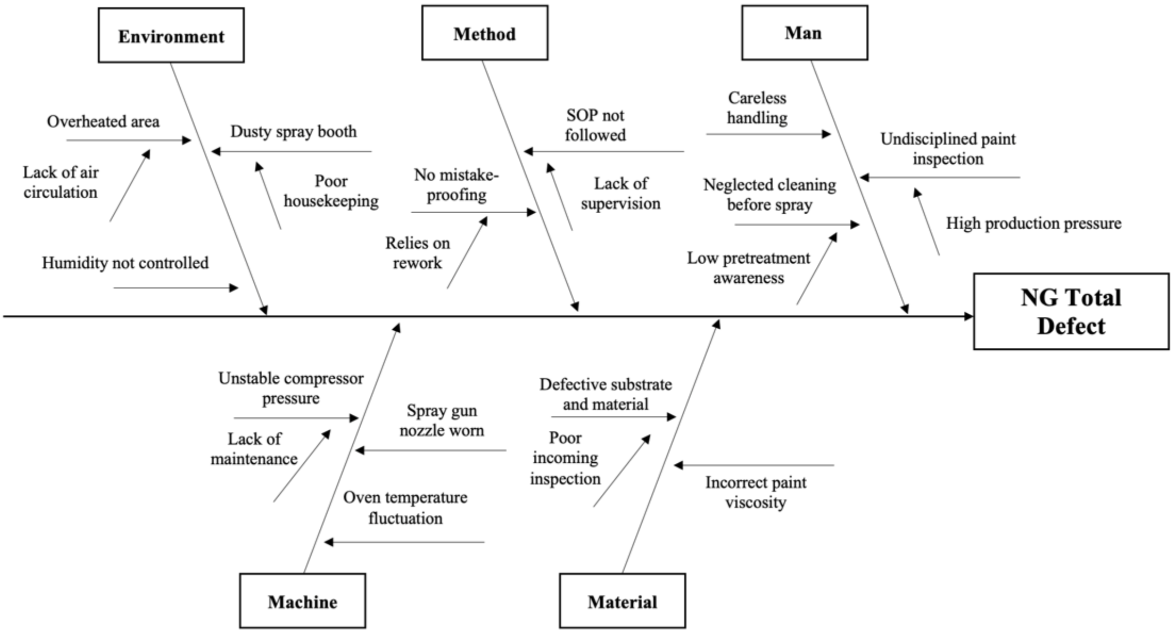

Figure 1. Fishbone Diagram of NG Total Defect

The results of root cause analysis of the method factor show that there is a possibility of inconsistency in the implementation of SOPs by some operators, such as SOPs that should serve as a reference in executing spray techniques, spray distance, and inspection steps. Weak supervision from direct superiors or supervisors also contributes to this issue because no direct follow-up or correction is carried out during the process. In addition, the absence of a mistake-proofing system (poka-yoke) in the work area causes repeated errors and prevents them from being systematically avoided. Under such conditions, quality control relies more on the rework process than on efforts to prevent defects from the beginning, resulting in repeated mistakes in the next period.

Next is the analysis of the material factor. The use of paint materials with viscosity that does not meet standards becomes one of the contributors to NG Total defects. This mismatch is caused by the inconsistency in conducting viscosity tests before the painting process begins, resulting in paint that is too thick and unable to spread evenly, producing a final surface that does not meet quality standards, including over paint and severe under paint defects. In addition, it was found that the base material or metal substrate to be sprayed sometimes already has physical defects from the beginning, such as fine scratches, small dents, or invisible contamination. This occurs because the incoming inspection process is not conducted thoroughly or in detail, allowing defective material to pass into the painting stage. Defects on the substrate or mismatched paint eventually result in a final product that cannot be repaired through rework and is directly categorized as NG total.

From the machine factor, it was found that several machine conditions in the production line do not support the stability of the painting process. One of the main root causes is the condition of spray gun nozzles that are worn or dirty due to lack of daily inspection and cleaning. Nozzles that are not in optimal condition cause uneven paint distribution, resulting in surface defects that are difficult to correct. In addition, unstable air pressure in the compressor was found, which is caused by a lack of regular preventive maintenance. This instability directly impacts the irregularity of paint flow during spraying, increasing the risk of under paint or severe bubbles that lead to NG total. Another problem is found in the stability of the drying oven temperature, where inaccurate control settings cause temperature variations during the drying process. If not properly addressed, this can result in serious defects such as large bubbles or paint that does not adhere perfectly to the material.

Observations in the production area show that the discovery of a significant amount of dust, especially in the spray booth area, becomes one of the root causes of NG total defects. This is caused by weak housekeeping programs and ineffective air circulation control. Dust particles that stick to the surface of materials before or during the painting process can disrupt paint adhesion, preventing the paint from sticking well to the surface and potentially resulting in severe defects that are difficult to fix. In addition, the excessively hot working area temperature due to suboptimal ventilation and cooling systems accelerates the drying of paint before its time, causing uneven paint distribution and increasing the risk of defects such as large bubbles or cracked paint layers. Uncontrolled air humidity also becomes a contributing factor to serious defects, as high humidity levels can interfere with the quality of the paint layer and cause imperfections in the final result.

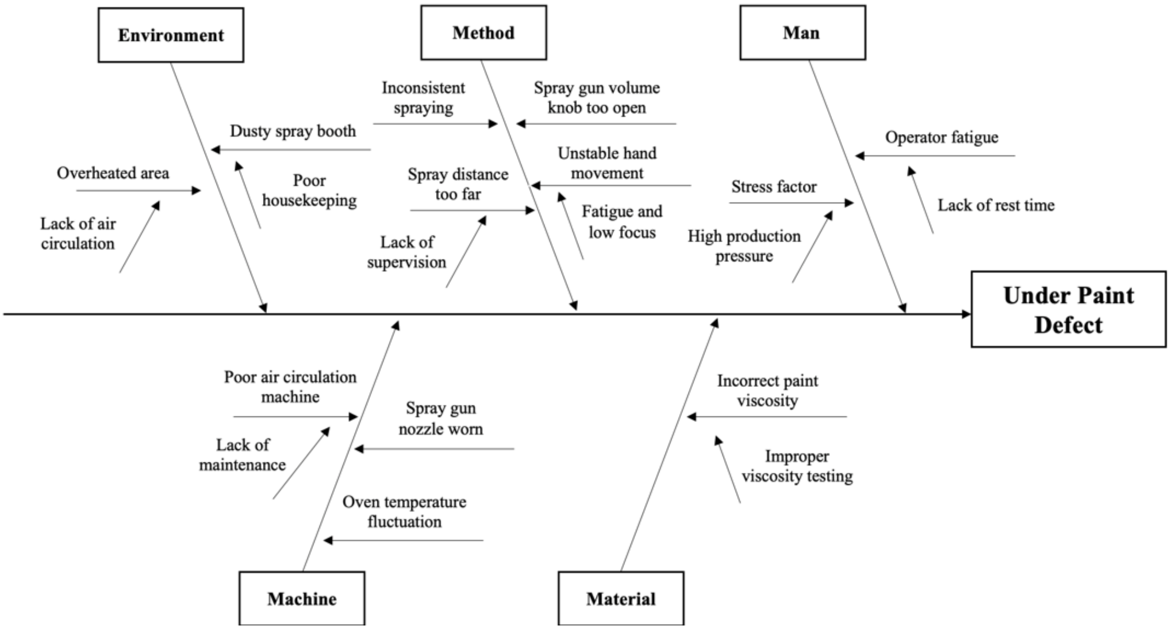

Figure 2. Fishbone Diagram of Under Paint Defect

Figure 2 shows the analysis results of the under paint defect, which groups various possible causes into five main factors. The human factor is a cause of Under Paint defects, in which the physical and psychological condition of the operators during the painting process has an impact on the quality of the paint layer. Based on discussions with the operator and field observations, it was found that operator fatigue due to lack of rest time is the cause of the decline in consistency in spraying techniques. This fatigue leads to reduced focus, unsteady hand movements, and irregularity in spray distance and direction, resulting in paint layers that are too thin. In addition, high production target pressure also creates stress that drives operators to work in a rushed manner and tends to ignore quality aspects. This combination of physical fatigue, psychological pressure, and minimal control over work speed makes the human factor a significant contributor to the occurrence of under paint defects that do not meet quality standards.

From the method factor, it was found that inconsistency in spraying techniques is the main root problem in this category. This factor is also related to the human factor. Operators often do not apply work methods consistently, such as variation in hand movement patterns, spray direction, and speed during the painting process. This is exacerbated by the improper setting of spray volume. The spray gun volume knob being too wide open causes uncontrolled paint distribution and uneven thickness. Additionally, spraying from a distance that is too far from the material surface also becomes an uncorrected habit, which results in thin paint layers. These issues should be minimized through more active supervision, but weak control in the field causes work practices that deviate from the standard to continue. As a result, the same mistakes keep recurring in the next processes, and the defects remain unresolved.

From the analysis of the material factor, it was found that the main root cause in this category is the use of paint with viscosity that does not meet the standard. This discrepancy occurs because viscosity testing is not carried out properly or is even ignored before the painting process begins, so paint that is too thick cannot spread evenly on the material surface. Paint layers that do not spread properly will result in areas that are too thin (under paint) and do not meet the expected thickness specification. This viscosity mismatch is not only caused by operator negligence but also indicates weak standards for material testing procedures before the production process. In the long term, the use of materials with uncontrolled physical characteristics will continue to increase the risk of recurring under paint defects.

The machine factor also significantly contributes to the occurrence of under paint defects. The analysis results show that several equipment conditions directly affect the thickness of the paint result. One of the root causes is worn or dirty spray gun nozzles, which result in uneven spray patterns and inconsistent paint distribution. This condition occurs due to a lack of routine inspection and equipment cleaning, so spray gun components are not always in optimal condition. In addition, it was found that temperature fluctuations in the drying oven also affect the final result of painting. Ovens that are unable to maintain stable temperatures have the potential to cause paint layers to dry too quickly or too slowly, both of which can result in thickness not meeting standards. Another related issue is the suboptimal performance of the air circulation machine, which is responsible for maintaining airflow in the spray booth area. If this machine does not function properly due to lack of maintenance, it can cause disturbances in the direction and consistency of paint spraying.

The environmental factor also contributes to the occurrence of under paint defects in the spray painting process. It is known that several environmental factors that cause NG total defects also directly affect the emergence of Under Paint defects. One main factor is the dusty working area condition, caused by weak housekeeping programs and suboptimal cleanliness control in the spray booth area. Dust particles floating in the air or sticking to the material surface before painting can interfere with paint adhesion, so the paint layer does not adhere properly and results in uneven thickness. In addition, inadequate ventilation in the spray booth area causes airflow disruption during painting, which can affect the direction and distribution of paint spray, resulting in some surface areas becoming under paint. Poor lighting in the working area also hampers operators in accurately monitoring paint thickness during the spraying process. On the other hand, excessively hot area temperatures due to poor air circulation cause the paint to dry before it spreads perfectly on the surface, increasing the risk of overly thin paint layers. Therefore, these environmental factors, which previously also contributed to NG total defects, have proven to significantly affect the stability and quality of paint thickness, and need to be a focus of improvement efforts to enhance the quality of the painting results.

b. **Failure Mode and Effect Analysis (FMEA)**

The next step is to conduct risk evaluation using the Failure Mode and Effect Analysis (FMEA) method. This method aims to assess the risk level of each potential failure based on three main parameters: the severity of the impact (Severity), the frequency of occurrence (Occurrence), and the ability to detect it (Detection). By multiplying these three values, a Risk Priority Number (RPN) is obtained, which is used to determine the priority of corrective actions. The smaller the RPN value, the lower the level of risk. Through this approach, it is expected that effective and efficient improvement steps can be established to reduce the defect rate in the spray painting process at PT Tritek Indonesia. Data for the FMEA were collected through a combination of direct observations on the spray painting line, review of quality control records, and semi-structured interviews with QA and QC managers, production manager, and spray painting operator. The FMEA scoring was conducted through interviews with the production manager, after the exploration of the main root causes of each defect type.

Table 1. FMEA Analysis for NG Total Defect

Potential Failure Mode	Potential Effects of Failure	S	Potential Cause of Failure	O	Current Control	D	RPN
NG Total (product cannot be reworked)	Product rejected; production cost loss	8	Inconsistent paint thickness inspection by operator	6	Visual inspection work instruction; final check SOP	5	240
	Poor adhesion; severe surface defect	6	Material not cleaned before painting	7	Pre-spraying cleaning procedure; pretreatment checklist	7	294
	Severe surface defect (e.g. bubbles)	5	Spray gun nozzle is worn or dirty	5	Scheduled spray gun maintenance; daily equipment check	5	125
	Irregular paint distribution	5	Unstable air pressure from compressor	3	Daily pressure check; routine compressor maintenance	5	75
	Improper curing; peeling or bubbles	6	Fluctuation in oven temperature	6	Regular oven calibration; digital temperature monitoring	1	36
	Paint not adhering properly	7	Dusty spray booth area	5	Routine housekeeping program; spray booth cleanliness supervision	1	35
	Uneven coating application	5	Overheated work area	6	Ventilation and temperature control in spray area	1	30
	Paint film disruption (e.g. bubbling)	4	Uncontrolled humidity	4	Humidity measurement; ventilation and exhaust system	1	16
	Coating does not meet standard	6	Incorrect paint viscosity	3	Paint viscosity testing before spraying; material control SOP	2	36
	Defect originates from substrate	7	Substrate defect during incoming	2	Incoming material inspection; visual material screening	2	28

Source: processed data

The results of the FMEA analysis on the NG total defect type indicate that the highest risk causes come from the human factor and the lack of control and supervision in the implementation of work procedures. The cause with the highest Risk Priority Number (RPN) is unclean material before painting, with an RPN value of 294. This condition shows that failure to consistently carry out the pretreatment process has a major impact on the occurrence of serious defects. Although the company already has cleaning procedures and a checklist in the pretreatment process, the effectiveness of its implementation is still low, compounded by low operator awareness and weak daily supervision.

The second cause with a high RPN is the operator's lack of discipline in inspecting paint thickness, with an RPN value of 240. Inaccuracy in conducting thickness inspections causes products to fail to meet quality standards and are directly classified as NG total. Although there are work guidelines and SOPs for visual inspection, the lack of standard internalization and pressure from production output targets cause this procedure to be implemented inconsistently and disorderly. The final quality control system, which relies solely on visual inspection, has proven insufficient to ensure quality; it needs to be complemented by the development of a disciplined and well-supervised work culture.

Other causes with fairly high risk values are worn or dirty spray gun nozzles (RPN = 125) and unstable oven temperatures (RPN = 75). These two causes are related to the maintenance of equipment and production machines. The company has issued a preventive maintenance schedule and an oven temperature calibration system, but irregularities are still found in their implementation. The lower RPN values for machine-related factors compared to human-related causes indicate that technical irregularities are not the dominant factor, but they do exacerbate process instability if operators are unable to detect potential failures early.

Several causes with low RPN values, such as uncontrolled humidity, non-compliant paint viscosity, and defective material from the start, indicate that the existing control systems (such as material inspection and humidity measurement) are still quite effective in identifying failures before they affect the final product. Therefore, although they still need to be monitored, these causes are not prioritized in the initial improvement actions.

Table 2. FMEA Analysis for Under Paint Defect

Potential Failure Mode	Potential Effects of Failure	S	Potential Cause of Failure	O	Current Control	D	RPN
Under Paint (coating layer too thin)	Fails visual inspection; does not meet thickness spec	8	Inconsistent spraying technique	5	SOP for spraying; operator technical training	5	200
	Uneven paint coverage	7	Unstable hand movement	2	Daily work briefing; supervisor observation	5	70
	Incomplete coating in certain areas	8	Spray distance too far	1	Standardized spray distance guide; process monitoring	1	8
	Poor coating distribution	6	Worn or dirty spray gun nozzle	2	Equipment cleaning before process; nozzle inspection checklist	1	12
	Adhesion failure or visible base material	8	Incorrect paint viscosity	7	Paint viscosity test (viscosity cup) before spraying	1	56

Potential Failure Mode	Potential Effects of Failure	S	Potential Cause of Failure	O	Current Control	D	RPN
	Surface looks patchy or thin	5	Overheated work area	3	Temperature and airflow control; ventilation system	1	15
	Adhesion issues due to contamination	5	Dust in spray area	5	Area cleanliness checklist; daily housekeeping routine	5	125
	Excessive variation in paint flow	6	Spray gun volume knob too open	2	Standard setting checklist; equipment setup SOP	7	84
	Operator loses concentration	5	Operator fatigue or stress	1	Work rotation schedule; rest period management	5	25
	Uncontrolled execution	5	Lack of floor-level supervision	2	Regular line monitoring; supervisor presence during spraying	1	10

Source: processed data

Table 2 presents the FMEA analysis results for the Under Paint defect, showing that the highest-risk causes are again dominated by human factors, particularly related to technical skills and consistency in executing the painting process. The cause with the highest Risk Priority Number (RPN) is inconsistent spraying technique (RPN = 200). This condition indicates that although the company has standard painting procedures, operator skills in maintaining spray distance, hand movement direction, and paint application speed are still not uniform. Factors such as fatigue, production target pressure, and lack of supervision further worsen the inconsistency in techniques, which directly affects the paint thickness not meeting the standard.

The next cause is a dusty work area, with an RPN of 125, which shows that environmental factors also significantly contribute to the occurrence of Under Paint defects. Dust adhering to the surface of the material before painting can disrupt paint adhesion and cause the paint layer to not adhere properly. Although a housekeeping program already exists in the production area, its implementation is still inconsistent, and there is no daily area audit to ensure workplace cleanliness before the process begins. This indicates that the environmental control system is not functioning properly.

Meanwhile, causes such as non-compliant paint viscosity have a lower RPN value (RPN = 56), but still require attention because technically they can cause uneven paint distribution. Paint with excessive viscosity will result in slow flow and uneven adhesion on the surface, which potentially increases the under paint area. Although viscosity testing procedures have been established, discipline in field implementation remains a challenge. Other causes such as worn spray gun nozzles, passive field supervision, and uncontrolled spray volume have relatively low RPNs and are not included in the early-stage improvement priorities, but they remain secondary risks that must be regularly monitored.

Overall, the findings from the Fishbone Diagram and FMEA analyses show that the majority of the root causes of defects (both NG total and under paint) originate from human factors and weak daily process control. This closely correlates with the highly extreme defect fluctuation patterns from day to day, as identified in the SPC analysis. The unpredictable variation in defect proportions, even exceeding the Upper Control Limit (UCL) and Lower Control Limit (LCL), indicates that the process is still heavily dependent on individual operator behavior and is not supported by strong preventive actions. Based on in-depth interviews with the production manager, it was revealed that inconsistencies in spraying techniques, inspection negligence, and the absence of follow-up documentation have caused the process to become unstable and difficult to predict in terms of performance. In the interview, the Production Manager stated, "When the operator's performance drops or they are overloaded, the impact on quality is immediately felt. Because everything is still manual and there's no system ensuring the standards are implemented consistently each day. The operators also lack motivation and initiative when they encounter problems, sometimes they don't even communicate them properly. And even when improvements are made, they're done spontaneously without any documentation at all." This statement reinforces the conclusion that the main root cause of process instability is a weak work system that depends on individuals, rather than a structured control system. Therefore, the findings from the Analyze Phase become a crucial foundation in designing improvement solutions.

Improve Phase

After identifying the root causes and analyzing risk levels through the Fishbone Diagram and Failure Mode and Effect Analysis (FMEA) methods, the next stage is the Improve Phase. This phase focuses on designing effective solutions to eliminate or reduce the impact of the main defect causes that have been identified, particularly the two dominant types of defects: NG total and under paint. To ensure the effectiveness and efficiency of the improvements, this stage will concentrate on developing solutions for the top 5 causes with the highest RPN values (highest risk). With this strategy, it is expected that the major contributors to process performance decline can be addressed with relatively few improvement efforts.

Table 3. Proposed Solution

No	Defect Type	Main Cause	Proposed Solution
1	NG Total	Material not cleaned before painting (RPN = 294)	Implementation of a daily pretreatment checklist to be signed by operator and verified by supervisor
2	NG Total	Undisciplined inspection of paint thickness (RPN = 240)	Paint thickness inspection system
3	Under Paint	Inconsistent spraying technique (RPN = 200)	Development of spray painting support equipment
4	NG Total	Worn/dirty spray gun nozzle (RPN = 125)	Implementation of preventive maintenance schedule and spray gun nozzle inspection
5	Under Paint	Dusty work area (RPN = 125)	Implementation of 5S principles

Source: processed data

a. **Pretreatment Checklist**

Material that is not properly cleaned before the painting process is the most critical factor causing NG total defects. Although the company already has a pretreatment SOP, its implementation in the field is not always carried out with discipline. Therefore, the implementation of a daily pretreatment checklist is proposed, which must be filled in by the operator and verified by the production supervisor as an effort to tackle this issue. The pretreatment checklist functions as a systematic tool to ensure that all pretreatment steps are carried out according to procedures before the material enters the painting stage.

The implementation of checklists has been proven to be one of the most effective methods in error management across various industries such as manufacturing, aviation, and healthcare. Checklists serve several key functions, including helping with memory recall of important steps, standardizing work processes, and increasing adherence to best practices. In the context of manufacturing, checklists play a crucial role in reducing process variation caused by human error and serve as tools for direct quality verification and control in the field (Hales and Pronovost, 2006). Checklist implementation also supports improved individual and team accountability, as every task listed must be completed and confirmed. In addition, checklists simplify troubleshooting when product defects occur because systematic recording allows easier root cause tracing.

Moreover, direct involvement of the supervisor at the pretreatment workstation is also necessary to promote a culture of discipline among operators in complying with SOPs. Supervisors are also responsible for providing immediate feedback and coaching when operator errors are found. This direct involvement is also expected to strengthen communication between operators and supervisors. A light monitoring system in the form of visual controls in the pretreatment area can also help process consistency, such as by giving visual labels or markers on materials that have been cleaned to standard before being transferred to the painting booth. This visual approach functions as a simple quality control method that is easy to observe, thus helping ensure the process is followed correctly and minimizing errors.

With the proposed improvement using this approach, it is expected that the consistency of material cleanliness before painting can be maintained, so that the potential for NG total defects caused by surface contamination can be significantly reduced. This solution is also considered realistic to implement, as it does not require investment in additional tools, but rather relies on strengthening documentation systems and work discipline.

Inspection in the checklist is not carried out for each part individually, but rather by process unit, namely per jig, where one jig consists of several parts (20–50 material units) that are processed together in one pretreatment cycle. Although PT Tritek Indonesia currently does not apply a sampling system, the documentation of this checklist remains an important initial step in building a culture of operational discipline. In the future, historical data from this checklist can be utilized as the foundation for developing a more efficient and sustainable sampling-based inspection system.

b. **Paint Thickness Inspection System**

The proposed solution to address irregularities in paint thickness inspection is an integrated inspection system composed of several components: daily thickness inspection checklist, periodic training, measurement tool calibration, and control of inspector fatigue.

- **Daily Paint Thickness Inspection Checklist**

  The implementation of a paint thickness inspection checklist aims to ensure that all inspection processes are documented. Operators are required to complete the checklist form each time a measurement is taken. This form records material data, inspection points, measurement results (in microns), and verification of compliance with technical specifications (e.g., 30–50 µm). This proposal aims to prevent errors due to negligence, train operational discipline, and provide a basis for quality trend evaluation by the QA team. According to Hales and Pronovost (2006), checklist implementation has proven effective in reducing the risk of cognitive errors, especially in repetitive tasks under pressure or fatigue.

  Considering the high production volume at PT Tritek Indonesia, which can reach thousands of parts per day, recording measurement results one by one for all parts is not feasible to perform efficiently. Therefore, the checklist is filled in only at critical points that represent process conditions, such as at the beginning, middle, and end of each shift, or based on several samples per production lot. This implementation is expected to be the first step toward a more structured and efficient sampling-based inspection system in the future, while also ensuring that the measurement process remains well-documented.

- **Periodic Inspection Training**

  Regular retraining is necessary to improve the competency of all inspection operators. The training covers understanding paint thickness standards, proper measurement techniques using coating thickness gauges, self-calibration, and visual recognition of defects caused by non-compliant thickness. Training is also supplemented with a defect visual library to reinforce understanding. According to Melchore (2011), this approach is essential because many inspection errors do not stem from a lack of tool knowledge but rather from insufficient understanding of standards and lack of visual training. His findings also emphasize the use of visual materials and hands-on practice to improve inspection accuracy in non-automated processes.

- **Addition of Micro-Breaks**

  Fatigue can affect precision and concentration in both measurement and visual inspection. Therefore, additional rest time is necessary for inspection operators. The maximum continuous working time is set to 30 minutes, followed by a 5-minute break before continuing with the inspection process. This proposed solution aligns with the findings of Tjolleng et al. (2023), which show that visual inspection performance declines significantly due to eye fatigue and boredom after more than 30 minutes. With this control, the risk of inspection errors caused by human factors can be minimized.

c. **Development of Spray Painting Assistive Tools**

The third-largest contributing cause of defects, especially under paint, is the inconsistency in spraying techniques among operators. The thickness and evenness of the paint layer on the material are highly influenced by variations in distance, angle, and spray direction. This issue is classified as human-dependent variability, which may be difficult to resolve through training or instruction improvement alone.

The proposed solution is the development of spray painting assistive tools designed to make the manual painting process more controlled. This solution aims to help operators maintain consistent spraying distance and direction through a combination of features such as a spray gun support arm, a rotating material platform with a fixed height, shield panels to prevent overspray and wind disturbance, and a visual spray distance guide.

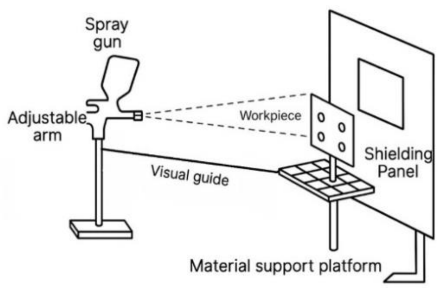

Figure 3. Prototype of Spray Painting Assistive Tool Development

Several features or tools have been developed to assist the spray painting process to become more consistent and less prone to variation:

- Spray gun support arm: This tool functions as an aid to maintain the direction and angle of the spray consistently during the painting process. With this tool, the operator no longer needs to fully bear the weight of the spray gun, thereby reducing arm and shoulder muscle fatigue that often causes inconsistencies in spray direction and distance.

- Material support platform: This support platform functions to ensure that the material remains stable at a predetermined height and distance (15–30 cm), so that the distance between the spray gun and the material surface can be consistently maintained. This feature is also equipped with a rotary mechanism that enables the operator to perform even painting across all sides of the material surface.
- Shield panel: This feature acts as a barrier on the sides and back of the painting area to prevent paint from spreading outside the target area (overspray) and to reduce disturbances from airflow that can cause uneven spray distribution. The shield panel also helps maintain consistent paint coverage on the material surface.
- Visual guide: This feature is in the form of an anodized aluminum measuring scale mounted parallel to the spray direction. The scale serves as a visual guide to help the operator maintain the ideal spraying distance between the spray gun and the material surface consistently.

d. **Spray Gun Inspection and Preventive Maintenance Schedule**

Another major cause of the high number of defects, particularly NG total, is the suboptimal performance of the spray gun, such as clogged nozzles (technical tool issues). This commonly occurs due to a weak inspection system and the absence of a consistently applied preventive maintenance schedule. Therefore, the proposed solution is the implementation of daily spray gun nozzle inspections and a regularly scheduled preventive maintenance program. This initiative aims to maintain the physical condition and performance of critical components such as the nozzle, trigger, filter, and connector, ensuring they remain clean, unworn, and functioning according to spraying standards.

In addition to daily inspections, preventive maintenance of the spray gun and its components must be implemented on a scheduled basis to prevent early damage and sustain equipment performance. Outlines the key maintenance activities to be performed, ranging from external cleaning, trigger lubrication, nozzle and seal inspections, to replacement of worn components. The frequency of maintenance varies depending on the usage level and equipment condition, with intervals ranging from daily to quarterly. This maintenance schedule is adapted from equipment manufacturer guidelines such as Graco (2021) and Sames (2020), as well as best practices in the painting industry, which have shown that consistent preventive maintenance significantly reduces the risk of production defects and extends equipment life.

In addition to daily inspections, preventive maintenance of the spray gun and its components must be implemented on a scheduled basis to prevent early damage and sustain equipment performance. Table 5 outlines the key maintenance activities to be performed, ranging from external cleaning, trigger lubrication, nozzle and seal inspections, to replacement of worn components. The frequency of maintenance varies depending on the usage level and equipment condition, with intervals ranging from daily to quarterly. This maintenance schedule is adapted from equipment manufacturer guidelines such as Graco (2021) and Sames (2020), as well as best practices in the painting industry, which have shown that consistent preventive maintenance significantly reduces the risk of production defects and extends equipment life.

Table 4. Preventive Maintenance Schedule for Spray Gun

No	Maintenance Item	Description	Recommended Frequency
1	Clean exterior of spray gun	Wipe off residual paint and dirt from gun body	After each use

No	Maintenance Item	Description	Recommended Frequency
2	Flush internal channels (paint/air)	Use appropriate solvent to flush gun immediately after use	Daily / After use
3	Inspect nozzle and tip guard	Check for clogging, wear, or damage; clean or replace if needed	Weekly
4	Check spray pattern	Perform spray test to ensure uniformity and symmetry	Weekly
5	Inspect and lubricate trigger mechanism	Ensure smooth operation; apply light lubricant if required	Weekly
6	Check air cap and needle	Inspect for blockage, build-up, or damage	Monthly
7	Inspect internal seals and O-rings	Replace worn or brittle parts to avoid leaks	Monthly
8	Perform deep cleaning / disassembly	Disassemble main parts for full cleaning (nozzle, needle, valve)	Monthly or as needed
9	Inspect hose and connectors	Check for cracks, wear, or leaks in hose and fittings	Quarterly
10	Replace worn components	Replace nozzle, needle, packing set as per wear conditions	Quarterly / As needed

Source: processed data

Through the implementation of structured daily inspections and a preventive maintenance schedule for spray gun equipment, this is expected to serve as a strategic step in maintaining painting quality consistency on the production line. With the daily checklist form, operators can directly detect equipment conditions before use, allowing defects to be prevented from the outset. Meanwhile, regularly scheduled preventive maintenance helps sustain long-term equipment performance and prevent sudden breakdowns that could disrupt production flow. The combination of these two systems promotes a more preventive work culture and is expected to improve both process performance and output quality.

e. **5S Principles Implementation**

The 5S implementation in the painting process was carried out as part of workplace improvement efforts to support more stable production quality. Activities focused on organizing the painting area, grouping tools based on function, conducting regular cleaning, and establishing cleanliness standards and work discipline. All stages were conducted with direct involvement of the operators to foster structured and consistent work habits. This implementation aimed to reduce the potential for contamination, operational errors, and improve workflow that was previously hindered by an unorganized working environment.

Control Phase

The Control Phase ensures that all implemented solutions are executed consistently and align with the original objectives. Control activities include the use of checklists, internal audits, and periodic evaluations using DPMO and sigma level metrics to monitor defect reduction trends. All new procedures are documented as operational references and for retraining purposes. Evaluations are conducted at least every two weeks, involving the production and QC teams to review implementation, identify issues, and promote a culture of continuous improvement. This phase also serves as a foundation for gradually setting stricter quality targets.

DISCUSSION

In the Define phase, this study conducted a comprehensive assessment using direct observations on the production line, interviews with production managers, quality report reviews, and process mapping tools such as SIPOC, process maps, and flowcharts to understand baseline conditions. These findings align with Jou et al. (2022), who emphasized the importance of thoroughly identifying the process, product, suppliers, customers, and customer quality requirements in the Define phase. A similar approach was used by Srinivasan et al. (2014) in a Six Sigma study on automotive component painting, which began with process mapping and setting key quality parameters for defect reduction.

In the Measure phase, the study evaluated the initial performance of the spray painting process at PT Tritek Indonesia, revealing high DPMO values and low sigma levels, indicating quality far below industry standards. P-charts showed statistical instability from January to March, suggesting the presence of special causes affecting quality. These findings are consistent with previous studies, such as Setiawan et al. (2025), who reported low sigma levels and major defects in tractor painting, and Arsyad et al. (2025), who highlighted the importance of using control and Pareto charts in assessing initial process performance. The application of DPMO and sigma measurements at PT Tritek was effective for establishing a quality baseline and guiding further improvements, as similarly observed in Jou et al. (2022), who used DPMO and control charts to identify baseline metrics and critical defect categories, and in Srinivasan et al. (2014), who identified peel-off and blister defects in shock absorber manufacturing.

During the Analyze phase, this study identified the root causes of dominant defects, NG total and under paint, using fishbone diagrams and FMEA. Jou et al. (2022) also applied fishbone and FMEA tools to prioritize improvements in their Six Sigma project and successfully reduced process variation. The highest root causes were found in human factors, including undisciplined paint thickness inspection and inconsistent spraying techniques, as well as method-related factors such as SOP noncompliance and the absence of mistake-proofing. The highest RPN values were recorded for poor pretreatment (RPN = 294) and inconsistent thickness inspection (RPN = 240). This aligns with Srinivasan et al. (2014), who also found key painting issues in the shock absorber process originating from pretreatment and parameter variation (e.g., pH, temperature), with recommendations to tighten initial process parameters. Furthermore, Bangun et al. (2017) emphasized the importance of operator training and strict supervision to address human error, which was also found to be the main root cause in this study. Additionally, Zulkarnaen et al. (2023) noted that environmental and cleanliness factors significantly contributed to the high defect ratio in vehicle painting, reducing the sigma level from 2.76 to 2.12 before improvement through a DMAIC approach using FMEA and fishbone tools.

In the Improve phase, the study at PT Tritek Indonesia designed five key solutions to reduce dominant defects: (1) implementation of a daily pretreatment checklist, (2) paint thickness inspection system, (3) development of spray painting assistive tools, (4) routine maintenance schedules for spray gun nozzles, and (5) implementation of 5S principles. The daily pretreatment checklist aimed to ensure material cleanliness before painting. This approach was proven effective in Setiawan et al. (2025), where pretreatment control measures such as chemical titration, solution temperature, and nozzle condition significantly reduced NG defects in tractor painting. The paint thickness inspection system was designed to ensure products met technical specifications without over/under coating. Hales and Pronovost (2006) reported that the use of daily inspection checklists was effective in reducing cognitive errors, especially for repetitive tasks under fatigue or stress. To enhance inspection accuracy, retraining was also necessary, as Gramopadhye et al. (1997) demonstrated that retraining could improve precision even among experienced inspectors. In addition, introducing micro-breaks every 30 minutes, as proposed by Albulescu et al. (2022) and Tjolleng et al. (2023), was shown to significantly reduce visual fatigue and maintain focus, lowering the risk of inspection errors.

The development of spray painting fixtures aimed to increase efficiency and position stability during spraying. Puerta and Arenas (2021) found that multifunctional fixtures in automotive painting lines increased production capacity by up to 40% without compromising spray quality. Another solution, routine spray gun nozzle maintenance, focused on spray pattern consistency. Worn nozzles cause uneven paint distribution and visual defects. Rakesh et al. (2020) reported that nozzle wear alters pressure and paint flow direction, reducing atomization quality. Lastly, the implementation of 5S aimed to create a clean and organized work environment to support sustainable quality. The 5S approach was shown to improve operational efficiency by 11% and reduce defect rates significantly in lean manufacturing studies by Pawlak et al. (2023) and Jou et al. (2022) in the automotive sector.

The Control phase in Six Sigma methodology ensures that all implemented solutions are sustained and aligned with project goals. Singh and Khanduja (2014) highlighted the importance of daily checklists, scheduled internal audits, and routine briefings as operational controls to maintain compliance with new procedures. Implementation performance was also evaluated using quantitative metrics like DPMO and sigma level to monitor process stability (Rao et al., 2020). In addition, complete documentation, such as accessible SOPs and work instructions, was emphasized to ensure sustainability and serve as the basis for retraining (Setiawan, 2025). To support improvement sustainability, biweekly evaluations and cross-functional coordination meetings were recommended to promptly respond to deviations and foster a culture of continuous improvement (Singh and Khanduja, 2014). These approaches are consistent with the findings of Purba et al. (2021), who emphasized that the Control phase is not the end of improvement, but a foundation for continuous quality enhancement in manufacturing.

CONCLUSION

One of the main findings of this research indicates that the high defect rate in the painting process at PT Tritek Indonesia is caused by several factors identified during the *Analyze* phase. Five primary causes were found to contribute most significantly to the two major defect types—*NG total* and *under paint*—as revealed through the fishbone diagram approach and *FMEA* analysis. The first factor is material that is not properly cleaned before the painting process, which had the highest *RPN* value of 294. This is followed by operator inconsistency in conducting paint thickness inspections (*RPN* 240), inconsistent spraying techniques (*RPN* 200), dirty or worn spray gun nozzles (*RPN* 125), and dusty working area conditions (*RPN* 125), all of which increase variation in process results.

The process capability of the spray painting line at PT Tritek Indonesia remains at a low level and has not yet met the company's internal quality targets. Analysis during the *Measure* phase showed that the *DPMO* (*Defects Per Million Opportunities*) values were recorded at 116,160 in January, 89,553 in February, and 110,861 in March 2025. These values correspond to sigma levels of 1.19, 1.34, and 1.22, respectively. In addition, the control chart indicated that the process was unstable, with several data points falling outside the control limits—signifying the presence of uncontrolled variation. This overall analysis confirms that the process is still not capable.

Based on the root cause identification results, the analysis in the *Improve* phase proposed five improvement solutions to enhance production quality and reduce the defect rate. These five solutions include: (1) implementation of a daily pretreatment checklist, (2) application of the *5S* principles in the painting area, (3) a paint thickness inspection system, (4) development of a spray painting assistive tool, and (5) regular inspection and maintenance of the spray gun. The pretreatment checklist was selected as the top priority based on criteria such as effectiveness, cost, ease of implementation, and time to implement. All proposed solutions were then followed by an implementation plan and controlled through the *PDCA* (*Plan-Do-Check-Act*) cycle approach.

Therefore, the implementation of the *DMAIC* framework is expected not only to reduce defect rates and process variation but also to strengthen the quality control system in a sustainable manner.

REFERENCES

Statistik, B. P. (2024). *Number of motor vehicle by type (unit)*. https://www.bps.go.id/en/statistics-table/2/MTIxNCMy/manufacturing-value-added-as-a-proportion-of-gdp.html

Albulescu, P., Macsinga, I., Rusu, A., Sulea, C., Bodnaru, A., & Tulbure, B. T. (2022). "Give me a break!" A systematic review and meta-analysis on the efficacy of micro-breaks for increasing well-being and performance. *PLOS ONE, 17*(8), 1–27.

Badan Pusat Statistik. (2024). *Manufacturing value added as a proportion of GDP*. https://www.bps.go.id/en/statistics-table/2/MTIxNCMy/manufacturing-value-added-as-a-proportion-of-gdp.html

Badan Pusat Statistik. (2024). *Number of motor vehicle by type (unit)*. https://www.bps.go.id/en/statistics-table/2/NTcjMg==/number-of-motor-vehicle-by-type--unit-.html

Bangun, C. S., Maulana, A., Rasjidin, R., & Rahman, T. (2022). Application of SPC and FMEA methods to reduce the level of hollow product defects. *Jurnal Hasil Penelitian dan Karya Ilmiah dalam Bidang Teknik Industri, 8*(1), 12–16.

Dannels, S. A. (2018). Research design. In *The reviewer's guide to quantitative methods in the social sciences* (pp. 402-416). Routledge.

Farchiyah, S. (2021). Analisis pengendalian kualitas spanduk dengan metode Seven Quality Control (7QC) pada PT. FIM PRINTING. *Tekmapro: Journal of Industrial Engineering and Management, 16*(1), 36–47. https://doi.org/10.33005/tekmapro.v16i1.187

Gleeson, D., Dong, H., O'Leary, P., Schueller, J. K., & Hashimoto, H. (2022). Generating optimized trajectories for robotic spray painting. *IEEE Transactions on Automation Science and Engineering, 19*(3), 1380–1391. https://doi.org/10.1109/TASE.2022.3156803

Graco Inc. (2021). *Operator's manual: Air-assisted spray gun XTR5 and XTR7 models*. Graco Industrial Equipment Division. Retrieved from https://www.graco.com

Gramopadhye, A. K., Drury, C. G., & Prabhu, P. V. (1997). Training strategies for visual inspection. *Human Factors and Ergonomics in Manufacturing, 7*(3), 171–196.

Hales, B. M., & Pronovost, P. J. (2006). The checklist—a tool for error management and performance improvement. *Journal of Critical Care, 21*(3), 231–235.

Jacobs, F. R., & Chase, R. B. (2023). *ISE operations and supply chain management* (17th ed.). McGraw-Hill Higher Education.

Jou, Y.-T., Silitonga, R. M., Sukwadi, R., Lin, M.-C., & Chen, C.-C. (2022). Application of Six Sigma methodology in an automotive manufacturing company: A case study. *Sustainability, 14*(21), 14497. https://doi.org/10.3390/su142114497

Melchore, J. A. (2011). Sound practices for consistent human visual inspection. *AAPS PharmSciTech, 12*, 215–221.

Pawlak, S., Nowacki, K., & Kania, H. (2023). Analysis of the impact of the 5S tool and standardization on the duration of the production process: Case study. *Production Engineering Archives, 29*(4), 421–427.

Prakash, L. (2014). Fundamentals and general applications of hardmetals. In V. K. Sarin (Ed.), *Comprehensive hard materials* (Vol. 1, pp. 29–90). Elsevier. https://doi.org/10.1016/B978-0-08-096527-7.00002-7

Puerta, F., & Arenas, D. (2021). Implementation of multifunctional fixture for automotive painting line. *International Journal of Innovative Science, Engineering & Technology (IJISET), 8*(12), 1–5.

Purba, H. H., Nindiani, A., Trimarjoko, A., & Jaqin, C. (2021). Increasing sigma levels in productivity improvement and industrial sustainability with Six Sigma methods in manufacturing industry: A systematic literature review. *Advances in Production Engineering & Management, 16*(3), 307–325.

Pyzdek, T., & Keller, P. A. (2018). *The Six Sigma handbook* (5th ed.). McGraw-Hill Professional.

Rao, U. A., Elapanda, S., Raju, I. B., & Kumar, M. A. (2020). Six Sigma application in manufacturing special process: A case study on resistance welding. *International Journal of Advanced Research in Engineering and Technology (IJARET), 11*(7), 568–580.

Razzouk, E., Koncz-Horváth, D., & Török, T. I. (2024). Critical challenges in the anodizing process of aluminium–silicon cast alloys—A review. *Crystals, 14*(7), 617. https://doi.org/10.3390/cryst14070617

Sames Kremlin. (2020). *FPro manual spray gun – Maintenance guide*. Sames Technologies SAS. Retrieved from https://www.sames.com

Setiawan, A. W., Sulistiyowati, W., Jakaria, R. B., & Sukmono, T. (2025). Tractor paint quality control by integrating the Six Sigma method and Fail Mode and Effect Analysis (FMEA) at PT. XYZ. *International Journal on Orange Technologies (IJOT), 7*(3), 116–126.

Setiawan, S. A. (2025). Implementation of Six Sigma methodology to reduce high defect rate in rubber processing industry. *European Journal of Business and Management Research, 10*(1), 118–126.

Singh, B. J., & Khanduja, D. (2014). Perspectives of control phase to manage Six Sigma implements: An empirical study. International Journal of Business Excellence, 7(1), 88–111.

Srinivasan, K., Muthu, S., Prasad, N. K., & Satheesh, G. (2014). Reduction of paint line defects in shock absorber through Six Sigma DMAIC phases. *Procedia Engineering, 97*, 1755–1764. https://doi.org/10.1016/j.proeng.2014.12.327

Tjolleng, A., Chang, J., Park, J., Lee, W., Cha, M., Park, J., & Jung, K. (2023). Development of a human-friendly visual inspection method for painted vehicle bodies. *Applied Ergonomics, 106*, 103911.

Zulkarnaen, I., Kurnia, H., Saing, B., Apriyani, A., & Nuryono, A. (2023). Reduced painting defects in the 4-wheeled vehicle industry on product type H-1 using the lean six sigma-DMAIC approach. *Jurnal Sistem dan Manajemen Industri, 7*(2), 179–192.