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Analysis Of Defect Waste Reduction In Metal Forming Process Using Lean Six Sigma

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Abstract— This empirical study systematically examines defect waste in the metal-forming production of the reff D nose component at PT XYZ, where 2018–2023 data reveal a 4.6% average defect rate—equivalent to 15,745.65 DPMO and a sigma level of 4.03—far from the 1% (≤6,667 DPMO, 4.5 σ) quality target. A concise DMAIC (Define, Measure, Analyze, Improve, Control) framework was applied, integrating SIPOC mapping, Pareto analysis, Interpretive Structural Modeling (ISM), and 5 Whys Root-Cause Analysis to isolate five key defect drivers: raw-material variability, process-parameter deviations, machine wear, operator competency gaps, and environmental instability. Based on these insights, we propose targeted interventions—tighter material specifications, standardized parameter-optimization protocols, preventive-maintenance schedules, competency-based operator training, and environmental controls to drive defect reduction. Unlike prior research that applies Lean or Six Sigma tools in isolation, our novel integration of ISM structures causal interdependencies, producing a prioritized, aerospace grade improvement roadmap. Projected outcomes include a reduction below 10,000 DPMO (≥4.5 σ) and sustained compliance with stringent industry benchmarks, offering a replicable methodology for high-precision manufacturing environments.

Keywords— Defect Waste Reduction ; Metal Forming; Lean Six Sigma; DMAIC; Process Improvement.

I. INTRODUCTION

The aerospace industry is renowned for its uncompromising quality standards, where even the smallest defects in aircraft components can lead to severe safety risks and operational failures. In this high-stakes environment, the manufacturing process must be meticulously controlled to ensure precision and reliability[1]. Metal forming, as a key process in producing aircraft parts, plays a critical role in achieving the desired structural integrity and aerodynamic performance. Despite stringent quality control measures, the occurrence of defects in metal forming processes remains a significant challenge. At PT XYZ, recent production data revealed that the defect rate in the reff D nose component averages 4.6% over a five-year period (2018–2023), which far exceeds the company's target of 1%. This discrepancy highlights the urgent need for a systematic approach to identify and mitigate the root causes of defects, ensuring that the final products meet the high safety and quality requirements of the aerospace industry[2].

The central problem addressed in this research is the high defect rate observed in the metal forming process at PT XYZ, specifically in the production of the reff D nose component. Despite existing quality control protocols, the defect rate remains significantly above the acceptable threshold. This study seeks to answer the main question. How can the implementation of Lean Six Sigma methodologies reduce defect waste in the metal forming process? Addressing this question is critical, as even minor improvements in process efficiency and product quality can have substantial impacts on overall operational safety, customer satisfaction, and competitive positioning in the global aerospace market [3].

Lean Manufacturing focuses on the elimination of waste and enhancement of process flow by identifying and removing non-value-added activities. Six Sigma, on the other hand, employs rigorous statistical methods to minimize variability and defects, aiming for a target of 3.4 defects per million opportunities. Previous studies have successfully applied these methodologies across various manufacturing contexts, resulting in significant improvements in process performance. For instance, research by Wockman and Jones demonstrated that lean principles can reduce operational costs while simultaneously enhancing customer value [4] . Similarly, highlighted the effectiveness of Six Sigma in reducing defect rates in production environments. The integration of these two approaches—commonly known as Lean Six Sigma—has been shown to produce synergistic benefits, providing a comprehensive framework that addresses both process inefficiencies and quality issues [5]. Tools such as SIPOC (Supplier, Input, Process, Output, Customer) diagrams, Pareto analysis, Interpretive Structural Modeling (ISM), and the 5 Whys method for Root Cause Analysis (RCA) have been instrumental in these improvements and serve as foundational elements in this research.

The innovation of this research lies in its integrative approach, combining multiple Lean Six Sigma tools to address the multifaceted problem of defect waste in metal forming. Unlike previous studies that may have focused on isolated aspects of process improvement, this research provides a comprehensive, data-driven analysis that spans the entire production process. By applying advanced methodologies such as ISM and RCA within the DMAIC framework, the study not only identifies the root causes of defects but also proposes actionable strategies to enhance overall process efficiency. The findings are expected to contribute valuable insights to both academia and industry, offering a replicable model for defect reduction in high-precision manufacturing environments.

II. RELATED WORKS

A. Waste

Waste is any activity related to the use of resources that do not provide added value to the products produced. The seven wastes that were first triggered were overproduction, wastage of waiting time, wastage of transportation and material handling, wastage of inventory, in-process wastage, motion wastage, and production of defective products (producing defects) where the source of wastage was first introduced by Taiichi Ohno[6].

B. Lean Manufacturing

Lean Manufacturing is a managerial philosophy designed to enhance efficiency and eliminate waste throughout the production process. According to [7], Lean Manufacturing not only targets cost reduction but also seeks to maximize customer value by streamlining and optimizing processes. Research by [5] demonstrates that accurately identifying value enables firms to concentrate on those features most desired by their customers. Moreover, the study conducted by [8] finds that implementing lean management elevates product quality through stricter quality control and by actively involving employees in continuous-improvement initiatives. By empowering personnel to participate directly in problem identification, organizations can foster a culture of ongoing refinement that positively impacts the final product's quality. The principal objectives of Lean Manufacturing are outlined by [9] as follows:

a. Minimizing all forms of waste—whether time, effort, or materials—during production..
b. Producing goods precisely in accordance with customer orders.
c. Reducing costs while concurrently enhancing product quality.

Another significant benefit of Lean Manufacturing is the improvement of customer satisfaction. By centering operations on the value delivered to customers, companies can respond more swiftly and effectively to market demands and customer expectations. As noted by [10] applying Lean Manufacturing principles helps organizations align production more closely with market demand, thereby achieving greater operational agility and responsiveness.

C. Six Sigma

The implementation of Six Sigma represents a strategic, systematic methodology that leverages rigorous data collection and statistical analysis to identify root causes and determine ways to minimize defect rates. Six Sigma is also regarded as an innovative management tool designed to supersede Total Quality Management (TQM), which traditionally focuses on holistic quality control across the entire system [11]. A crucial distinction between Six Sigma and TQM lies in their objectives: TQM emphasizes meeting minimum quality standards, whereas Six Sigma not only ensures those baseline requirements but also concentrates on driving performance improvements. The Six Sigma methodology is founded upon several core principles—process improvement, statistical methods, system production management, continuous enhancement, and finance-related optimization [12].

D. Lean Six Sigma

According to [5] Lean Six Sigma represents an integration of Lean and Six Sigma, defined as both a business philosophy and a systemic, systematic approach to identifying and eliminating waste—or non-value-added activities—through radical continuous improvement aimed at reaching a Six Sigma level. It achieves this by employing a pull system to flow products (materials, work-in-process, and outputs) and information from internal and external customers, with the goal of producing no more than 3.4 defects per million opportunities. A disciplined and rigorous application of this combined methodology yields significant performance enhancements.

E. Interpretive Structural Modeling

Interpretive Structural Modeling (ISM) is a modeling technique used to analyze the elements of a system and represent them graphically, illustrating direct relationships among elements and their hierarchical levels. It is termed interpretive because the inter-element relationships within the problem under study are derived through structured discussions with subject-matter experts [13]. It is called structural because it captures a complex system by organizing its components into carefully designed graphical patterns. By applying the ISM technique, ambiguous or poorly defined conceptual models are transformed into visible system representations, clearly depicting both the interrelationships and the structural hierarchy of elements in a graphical format [14].

III. METHOD

The study employs a mixed-methods approach that integrates both quantitative and qualitative techniques. The research is structured around the DMAIC (Define, Measure, Analyze, Improve, Control) framework a well established method for process improvement in manufacturing.

3.1 DMAIC

In the Define phase, the research begins by meticulously mapping the entire production process through the development of a comprehensive SIPOC diagram, which outlines the relationships between suppliers, inputs, processes, outputs, and customers.

This mapping serves as a visual framework to identify all critical components and interactions within the manufacturing system [4]. Concurrently, baseline defect rates are established by analyzing historical production data spanning from 2018 to 2023, which provides a clear benchmark for measuring process performance and identifying key areas where defects are most prevalent.

Moving into the Measure phase, the study systematically gathers both quantitative and qualitative data. Primary data is collected through direct observations on the shop floor and in-depth interviews with operators, engineers, and quality control personnel, offering real-time insights into operational challenges and inefficiencies. Simultaneously, secondary data is extracted from detailed production records and defect logs, allowing for the calculation of key performance metrics such as Defects Per Million Opportunities (DPMO) and sigma levels [15]. In addition to these methods, the research employs Interpretive Structural Modeling (ISM) as an analytical tool during the measurement process. ISM is utilized to structure and visualize the relationships and interdependencies among various process variables; its function is to reveal the hierarchical order of factors that contribute to defect occurrences[6]. This structured approach not only refines the data collection process but also lays the groundwork for a more focused analysis in subsequent phases.

In the Analyze phase, the collected data is rigorously examined to identify the most critical areas of concern. Statistical tools, such as Pareto analysis, are employed to prioritize defect types by highlighting those that contribute most significantly to overall waste [14]. Further, Root Cause Analysis (RCA) is performed using the 5 Whys method, which delves deep into the underlying causes of recurring defects. To complement these methods, Interpretive Structural Modeling (ISM) is utilized to elucidate the interrelationships and hierarchical dependencies among the identified variables, thereby providing a clearer picture of the process dynamics and pinpointing specific areas for intervention.

During the Improve phase, the insights gained from the analysis inform the development of targeted improvement strategies. Interventions are designed to address the key issues identified, such as enhancing raw material quality, optimizing process parameters, improving machine maintenance routines, and bolstering operator training programs [17]. These strategies are first tested in a controlled pilot environment to assess their effectiveness, with adjustments made as necessary based on feedback and observed outcomes. The pilot phase serves as a critical step in ensuring that the proposed changes are both practical and capable of yielding a sustainable reduction in defect rates, thus setting the stage for the subsequent Control phase where long-term monitoring and validation are established [18].

3.2 Data Collection

The study employs a mixed-methods approach that integrates both quantitative and qualitative techniques to identify Lean Six Sigma method for reduce defect quantity. Data collection is crucial for the success of this research and is divided into two main sources:

1. Primary Data :
   Real-time observation of the metal forming process at PT XYZ to document process flow and defect occurrences and collect qualitative insights from operators, engineers, and quality control personnel regarding process challenges and potential areas for improvement.
2. Secondary Data:
   - Production Records: Historical production data and defect logs from PT XYZ covering the period 2018–2023.
   - Quality Reports: Detailed defect reports that include defect types, quantities, and associated process parameters.

IV. RESULT AND DISCUSSION

The following table presents the total production figures and defect counts recorded from 2018 to 2023.

Tabel 1. Production and Defect Quantity

Year	Production (pcs)	Defect (pcs)
2018	213	15
2019	204	4
2020	151	6
2021	88	3
2022	84	0
2023	92	11
Total	832	39

Source : company archives

The following table provides data on the types of defects observed in the reff D nose sub-assembly within the metal forming production line.

Tabel 2. Defect type

Year	Defect Quantity		
	Edge	Etching	Part
2018	3	8	4
2019	0	3	1
2020	2	3	1
2021	1	1	1
2022	0	0	0
2023	2	8	1
Total	8	23	8

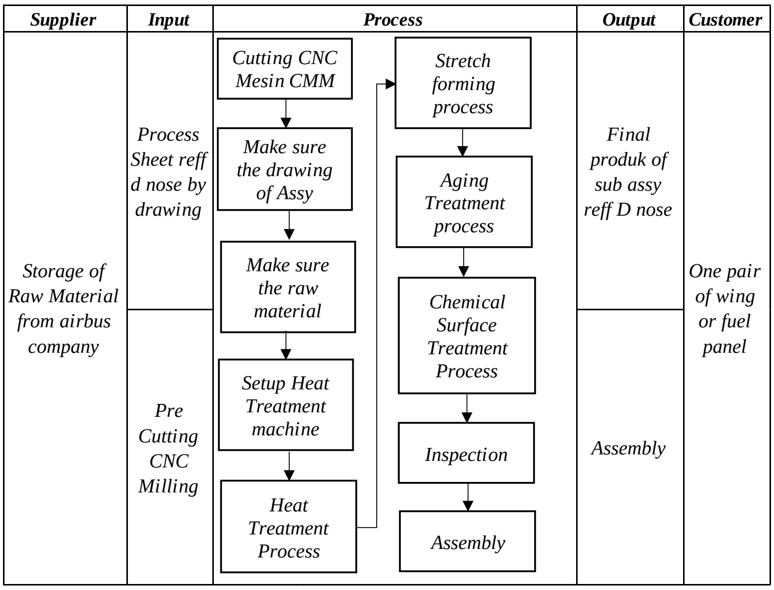
Source : company archives

Based on the two tables presented above, it can be observed that the most frequent defect is Etching, with a total of 23 units accounting for 58.9% of the defects. In contrast, both Edge and Part defects occur 8 times each, representing 20.51% per category. Overall, the defect rate is 4.6% of total production, which significantly exceeds the company’s target of 1%. This disparity indicates a critical need for corrective measures to reduce defect occurrences and prevent potential losses.

4.1 Define

The Define phase, the first stage of DMAIC, aims to clearly articulate the problem under investigation in this case, the assembly process of the reff D nose in the metal forming production line. To achieve this, a SIPOC (Supplier, Input, Process, Output, Customer) diagram is employed as a critical tool to map and visualize the entire production process, thereby establishing a solid foundation for subsequent analysis [19].

Table 3.
SIPOC Diagram



After mapping the production process of the reff D nose in the metal forming line, a Critical To Quality (CTQ) analysis will be conducted using a Pareto diagram to determine key quality attributes.

Table 3. Defect Type Percentage

No	Defect Type	Defect Quantity (Pcs)	Cumulative Percentage (%)
1	*Etching*	23	59%
2	*Edge*	8	21%
3	*Part*	8	21%
Total		**39**	**100%**

Source : company archives

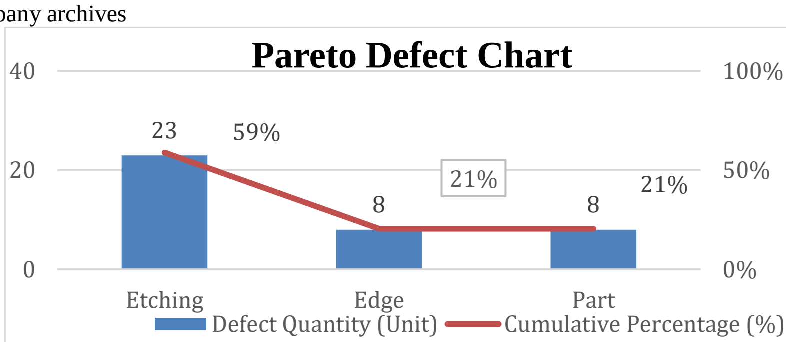


Figure 1. Pareto Chart

Based on the Pareto diagram above, the predominant defect is of the Etching type, accounting for 59.70% of the defects, followed by both Edge and Part defects at 21% each. These defects arise due to errors occurring during various stages of the manufacturing process. Consequently, the reff D nose production process will be thoroughly investigated to identify the primary causes and the variables that most significantly influence the occurrence of defects.

4.2 Measure

The Measure phase, the second stage of DMAIC, is designed to quantify the occurrence of defects and identify the primary causes of defects within the reff D nose sub-assembly production process in the metal forming line. During this phase, the operational performance of the system is assessed by calculating metrics such as Defects Per Million Opportunities (DPMO) and determining the sigma level.

Table 4. Sigma Level Value

Years	Production (Pcs)	Defect (Pcs)	CTQ	DPU	TOP	DPMO	SIX SIGMA
2018	213	15	3	0.0704	639	23474.18	3.4868
2019	204	4	3	0.0196	612	6535.95	3.9818
2020	151	6	3	0.0397	453	13245.03	3.7190
2021	88	3	3	0.0341	264	11363.64	3.7780
2022	84	0	3	0.0000	252	0.00	6.0000
2023	92	11	3	0.1196	276	39855.07	3.2524
TOTAL	832	39	18	0.283422	2496	94473.87	24.21788
AVARAGE	138.6667	6.5	3	0.047237	416	15745.64	4.036313

Based on the table, it can be concluded that the DPMO value remains relatively high at 15,745.65 defects. This figure, derived from the five-year average production data (2018–2023) and converted into a sigma level of 4.03, indicates that for every one million production opportunities, approximately 15,745.65 defects are likely to occur.

Given the high number of defects observed, it is imperative to implement corrective measures by employing a tool that identifies the key variables contributing to these defects. In this Measure phase, the Interpretive Structural Modeling (ISM) method will be utilized. In this stage, contextual relationships were established through a Focus Group Discussion (FGD) [11] involving two key stakeholders from the SPIRIT department. As a result, the variables influencing defect occurrence were identified and are presented in the following table.

Table 5. Defect Variabel

No	Variabel
A1	Raw Material Quality
A2	Process Parameter Settings
A3	Machine Condition
A4	Operator Competency
A5	Effective Communication and Coordination
A6	Production Environment Stability

Table 6. Structural Self Interaction Matrix

NO	A1	A2	A3	A4	A5	A6
A1		A	V	O	O	A
A2			V	V	A	A
A3				A	A	A
A4					V	V
A5						A
A6						

Information:

a) V indicates that element i affects element j

b) A indicates that element j affects element i

c) X signifies that element i affects element j and vice versa

d) O indicates that the elements i and j do not affect each other.

SSIM (Structural Self Interaction Matrix) is an important element in Interpretive Structural Modeling (ISM). The goal is to illustrate the relationships between elements in a complex system. Each element in the system is connected to all other elements, including itself. Then after the SSIM is already in place, the Reachibility Matrix is made.

Table 7. Reachibility Matrix

NO	A1	A2	A3	A4	A5	A6	DP	R
A1	1	0	1	0	0	0	2	3
A2	1	1	1	0	0	0	3	2
A3	0	0	1	0	0	0	1	4
A4	0	1	1	1	1	0	4	1
A5	1	1	1	0	1	0	4	1
A6	1	1	1	0	0	1	4	1
D	4	4	6	1	2	1		
L	2	2	1	4	3	4		

From the reachability matrix above, a structural model is derived that forms a network depicting the influence levels of various variables. Subsequently, the interrelationships among these variables are visualized using an ISM model in the form of a directed graph, where the most influential variables are positioned at the lower levels and the most affected ones at the upper levels [12]. This model facilitates a clear understanding of the hierarchical structure of variable influences, thereby enabling strategic decision-making based on well-defined relationships. The model is presented in the following figure.

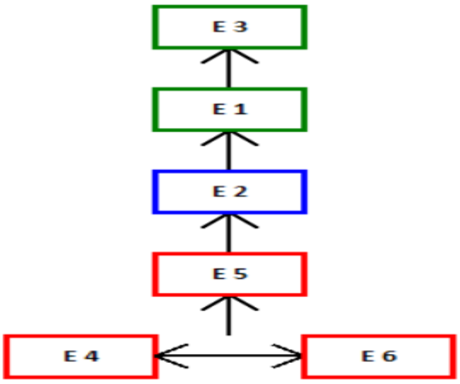


Figure 2. ISM Model

Based on the data analysis using the Interpretive Structural Modeling (ISM) method, it was determined that variable 4 (operator competency) and variable 6 (production environment stability) are the most influential factors within the system. These driving factors play a crucial role in preventing defects on the metal forming production line. This finding underscores that enhancing operator skills, strict adherence to standard operating procedures (SOPs), and maintaining a stable production environment such as effective control of temperature and humidity are fundamental to ensuring the quality of the final product.

During the measurement phase, an analysis will be conducted to identify the root causes of the most influential variables (variable 4: operator competency and variable 6: production environment stability) using Root Cause Analysis (RCA). The RCA tool employed in this research is the 5 Why method. In the subsequent stage, the underlying reasons for the occurrence of these variables will be analyzed, with the aim of providing effective improvement solutions to reduce defects in the production of the reff D nose on the metal forming production line.

4.3 Analyze

The following section explains the root causes of the issues related to variable 4 (operator competency) and variable 6 (production environment stability) using the 5 Why tool from the Root Cause Analysis (RCA) method [13]. In this study, RCA is applied exclusively to these critical variables, as they represent the conditions that most significantly affect the occurrence of defects in the reff D nose production process on the metal forming production line.

Table 8.
Root Cause Analysis variable 4 (operator competency)

Why	Question	Answer (Cause)

1 Why	Why does the defect occur?	The operator does not follow the Standard Operating Procedure (SOP) correctly.
2 Why	Why does the operator not follow the SOP correctly?	The operator does not fully understand the established work procedures.
3 Why	Why does the operator not fully understand the work procedures?	The training provided is not comprehensive and is not conducted regularly.
4 Why	Why is the training not comprehensive and not conducted regularly?	There is no structured training system and no periodic evaluation of operator competency.
5 Why	Why is there no structured training system and periodic competency evaluation?	There is no company policy requiring mandatory periodic training to improve operator competency.

Table 9. Root Cause Analysis variable 6 (production environment stability)

Why	**Question**	**Answer (Cause)**
1 Why	Why does the defect occur?	The production environment is unstable, causing variations in product quality.
2 Why	Why is the production environment unstable?	Temperature, humidity, and cleanliness in the production area are not consistently controlled.
3 Why	Why are temperature, humidity, and cleanliness not consistently controlled?	The monitoring and control system of the production environment is not functioning optimally.
4 Why	Why is the monitoring and control system not functioning optimally?	Environmental sensors and monitoring equipment are not properly calibrated or are malfunctioning, and routine inspections are lacking.
5 Why	Why are environmental sensors and monitoring equipment not calibrated or malfunctioning?	There is no structured preventive maintenance procedure, and insufficient attention is given to production environment management.

For variable 4, the analysis revealed that inadequate training is the primary issue. This deficiency is attributed to the absence of a structured training system and periodic evaluations of operator competency. The lack of such a system results in the absence of company policies mandating regular training, leaving operators without a strong foundation to perform their duties according to established standards. Consequently, the root cause of defects related to this variable is the lack of policies and a periodic training system that ensures operators maintain sufficient competency in executing standard procedures.

In contrast, for variable 6, it was found that production environment instability is the key factor contributing to variations in product quality and an increased defect rate. This instability is due to the uncontrolled environmental parameters—such as temperature, humidity, and cleanliness of the production area—that should be maintained within specific tolerances to ensure consistent production outcomes. The underlying issue in this environmental factor stems from a suboptimal monitoring and control system, which is primarily due to inadequate calibration and maintenance of the sensors and monitoring equipment used to control the production environment.

4.4 Improve

In the Improve phase, quality improvement actions are implemented to reduce the number of defects. Once the issues have been identified, the following corrective measures are undertaken:

1. Development of a Structured Training Program
   The Standard Operating Procedures (SOP) are revised by developing a comprehensive and structured training program. Each operator is provided with detailed training modules on work procedures and metal forming techniques.

Enhancing operator skills is expected to ensure consistent understanding and application of the SOP, thereby preventing operational errors.

2. Strengthening the SOP Compliance Monitoring and Evaluation System
The monitoring system is optimized by establishing daily audit mechanisms conducted by supervisors and production managers. With more rigorous oversight and periodic evaluations, adherence to SOPs is expected to improve significantly, minimizing the likelihood of employee errors [14].
3. Optimization of the Production Environment Monitoring System
The stability of the production environment is enhanced by installing real-time sensors to monitor critical parameters such as temperature, humidity, and workspace cleanliness. This system enables the team to promptly implement corrective actions and maintain consistency in the production process quality.
4. Preventive Maintenance Procedures for Monitoring Equipment
A structured preventive maintenance schedule is developed and implemented for sensors and other environmental monitoring devices. This procedure includes routine calibrations, daily inspections, and periodic environmental audits to ensure that all equipment functions optimally. As a result, the stability of the production environment parameters is consistently maintained, reducing variability in product quality.

V. CONCLUSION

The findings of this study lead to the following key conclusions are derived :

1. This study concludes that the current average DPMO of 15,745.65 ($\sigma = 4.03$) remains well above the sigma level ($\geq 4.5\ \sigma$) target, underscoring a critical quality gap. Accordingly, a comprehensive improvement plan consisting of tighter raw-material specifications, standardized process-parameter optimization protocols, preventive-maintenance schedules, competency-based operator training, and enhanced environmental controls will be implemented to reduce defects below the industry benchmark and bolster production reliability.
2. The study identifies that the main contributors to defects in the reff D Nose production are insufficient operator understanding of standard operating procedures and instability in the production environment. Root Cause Analysis using the 5 Whys method revealed that these issues stem from the lack of a structured and periodic training program as well as the absence of effective preventive maintenance for environmental monitoring equipment. With the implementation of the proposed improvement strategies, it is expected that the defect rate will significantly decrease, leading to a lower DPMO reduction below 10,000 and an increase in the sigma level ($\geq 4.5\ \sigma$) bringing process performance closer to the company's quality target and enhancing overall manufacturing consistency. By targeting these, PT XYZ can expect immediate gains in first-pass yield, fewer unplanned stoppages, and a reduction in rework and scrap costs.
3. Evaluation Lean Six Sigma based interventions including a structured operator training program, strengthened SOP compliance monitoring, optimized environmental control systems, and preventive maintenance protocols are expected to significantly enhance product quality by improving first-pass yields and ensuring process stability. These measures also contribute to cost reduction through decreased scrap and rework, while increasing equipment reliability and overall production efficiency. Moving forward, this integrated improvement framework can be applied to other metal-forming lines and further developed with real-time Industry 4.0 sensor integration to support adaptive and data-driven process control.

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