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Reducing Defects during Wrapping Process in Plastic Straw Manufacturing: A Six Sigma DMAIC Approach with FMEA Prioritization

Chaterine Alvina Prima Hapsari *, Ahmad Mumtaza, Ary Arvianto and Denny Nurkertamanda

Department of Industrial Engineering, Faculty of Engineering, Diponegoro University, Tembalang, 50275, Semarang, Central Java, Indonesia.

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Abstract

Quality is a crucial element in maintaining competitiveness within the manufacturing industry, especially in high-demand and globally competitive sectors, such as the production of plastic straws. Consistently meeting quality standards is essential for ensuring customer satisfaction, minimizing waste, and improving production efficiency. Inconsistent quality can lead to increased production costs, loss of customer trust, and reduced market competitiveness. This study examines quality control in the plastic straw production process at PT. XYZ by using the Six Sigma approach, specifically applying the DMAIC method. The research addresses recurring quality issues in the form of product defects that exceed the company's 1% maximum allowable reject rate, particularly in the wrapping process. In the Define phase, the wrapping process was identified as the Critical to Quality (CTQ) point contributing most significantly to overall defects. The Measure phase revealed a Defects Per Million Opportunities (DPMO) of 2,558.08 and an average sigma level of 4.3, showing a process with moderate capability. The Analyze phase used a Fishbone diagram to identify root causes of defects across five main factors: man, machine, method, material, and environment. The Improve phase applied Failure Mode and Effects Analysis (FMEA) to prioritize risks and suggest corrective actions based on their Risk Priority Number (RPN) values. The findings highlight that systematic analysis using Six Sigma tools effectively identifies critical quality problems and proposes targeted improvement strategies. Moreover, the results propose actionable recommendations focused on supplier quality, machine maintenance, operator training, and component reliability to address defects that occur during the wrapping process.

Keywords: Engineering; Six Sigma; Failure Mode and Effects Analysis; Plastic Straws; Quality Control; Defects

1. Introduction

In an era marked by rapid industrial advancement and increased market competition, quality has become a central pillar in determining a manufacturing company's long-term success and sustainability. As industries strive to meet diverse customer needs, global standards, and rising production targets, the ability to consistently produce high-quality products has shifted from a competitive advantage to a fundamental requirement [1]. The plastic packaging industry is no exception, as plastic straw is commonly used in the beverage sector. If it is not manufactured correctly and does not maintain its quality, it increases the health risk, such as the presence of phthalates and pathogenic bacteria on the product [2]. Moreover, considering sustainability issues, competitors of drinking straws are competing to introduce alternative materials that compare favorably to plastic straws in several key characteristics, such as biodegradability, mechanical properties, chemical-free properties, reusability, wetting stability, and cost-effectiveness [3].

In Indonesia, the plastic industry continues to grow significantly. As of 2022, plastic consumption per capita reached 22.5 kilograms, with total usage nearing 10 million tons per year and projected to grow annually by 7% [4]. With such

* Corresponding author: Chaterine Alvina Prima Hapsari

growth, companies face pressure not only to scale up production but also to ensure that their output quality meets stringent standards. Failure to control product quality can lead to increased operational costs due to waste and rework, reduced efficiency, lower customer satisfaction, and long-term damage to the brand's reputation [5].

PT. XYZ is a manufacturing company specializing in the production of plastic straws. Despite having an established quality management policy that sets the maximum allowable reject rate at 1% for each process, including extruding, flexible manufacturing, wrapping, and packing, the company has encountered significant challenges in maintaining this threshold. Internal data indicate that, over several production periods, defect levels in specific processes exceed the acceptable limit. During 2023, the extrude process experienced seven periods with a reject rate above 1% and recorded an annual average reject rate of 1.2%. The flexible manufacturing process had five periods exceeding the limit, with an annual average of 0.55%. The wrapping process had 11 periods, with an annual average of 1.56%, and the packing process had eight periods, with an annual average of 1.06%. These recurring quality issues suggest that uncontrolled variations and inefficiencies exist within the production processes. To address this challenge, a more systematic and data-driven approach to quality analysis and improvement is necessary.

Several research studies related to the production problem have been conducted. The problems that occurred in the production unit have been resolved by implementing the Six Sigma approach, specifically DMAIC, to enhance the effectiveness of the production process [6]. On the other hand, the rejection problem in the automobile filter manufacturing industry has been drastically reduced by implementing VSM, the Six Sigma approach (DMAIC), process capability, control charts, a Pareto Chart, and a Fishbone diagram [7]. A case study on defects in microlens manufacturing has also been successfully addressed by applying the Six Sigma approach, specifically through DMAIC, Pareto charts, experimental design, and MCDM, resulting in increased daily production rates and annual cost savings [8]. In general, Six Sigma focuses on reducing process variation and eliminating defects by employing statistical tools and structured problem-solving methods. The DMAIC cycle, one of the Six Sigma approaches, comprises Define, Measure, Analyze, Improve, and Control, serving as a roadmap for continuous process improvement [9].

The objective of this study is to analyze quality control in the plastic straw production process at PT. XYZ using the Six Sigma DMAIC methodology. The research aims to identify the most critical quality issues, determine their root causes, and propose feasible improvement actions to reduce the defect rate and enhance overall process capability. The hypothesis is that the systematic application of Six Sigma tools can support the identification of key process inefficiencies and lead to actionable recommendations that help reduce quality-related losses. This research is important for several reasons. First, it provides PT. XYZ with a structured diagnostic of its current production quality, identifying areas with the highest potential for improvement. Second, it offers a practical application of Six Sigma tools, such as the Fishbone diagram, Pareto chart, and Failure Mode and Effects Analysis (FMEA), which can be adapted for similar quality challenges in other production environments. Finally, by demonstrating how a systematic methodology can be applied in real-world manufacturing settings, the study contributes to the broader discourse on operational excellence and continuous improvement in Indonesia's industrial sector.

In conclusion, the study addresses a critical issue faced by plastic packaging manufacturing firms: maintaining consistent product quality in the face of operational and market pressures. By applying the Six Sigma DMAIC framework, the research aims to provide evidence-based insights that can guide PT. XYZ and similar companies are moving toward enhanced quality control and improved production performance.

2. Material and methods

2.1. Material

This research focuses on one of the products from PT. XYZ, the plastic straws that have a recurring defect problem. The detailed specification of the plastic straw produced by PT. XYZ is shown in Table 1.

2.2. Research Design

The research design applied in this study is a quantitative descriptive design. This classification is based on a structured and objective approach that uses measurable data to describe and analyze an existing problem. According to Creswell and Creswell [10], quantitative research is defined as an approach for testing objective theories by examining relationships among variables, involving measurable data analyzed through systematic procedures. In this study, the Six Sigma DMAIC methodology is utilized to identify and analyze defects, calculate performance metrics such as DPO (Defects Per Opportunities) and DPMO (Defects Per Million Opportunities), and propose improvements based on these measurements. The research design is descriptive because it aims to provide a detailed and factual account of the current condition without manipulating variables or exploring subjective meanings.

Table 1 Plastic Straw Specification in PT. XYZ

No.	Specification	Variant	Dimension
1	Length	125 ml packaging	134 - 135 mm
		200 ml packaging	164 – 165 mm
		250 ml packaging	180 – 181 mm
2	Thickness		19 – 20 microns
3	Diameter		3.9 – 3.95 mm

2.3. Methodology

The methodology employed in this research adheres to the Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) approach to enhance quality in the plastic packaging industry. In the Define phase, the primary objective is to understand the overall process and identify the key areas of concern [11]. A SIPOC diagram (Suppliers, Inputs, Process, Outputs, Customers) is developed to map the high-level process involved in producing plastic straws. This tool helps define the key processes, their sequence and interactions, and the customers involved in each process [12]. Based on the SIPOC diagram and the product-related issues or challenges, Critical to Quality (CTQ) characteristics are determined. These CTQs represent the key, measurable attributes that are essential to resolving product problems and meeting quality standards [13]. The identification of CTQs is crucial, as they serve as the foundation for the measurement and analysis phases that follow. In the Measure phase, data is collected to calculate Defects per Opportunity (DPO), Defects per Million Opportunities (DPMO), and the Sigma Level. These metrics provide a clear picture of current process performance, indicating whether quality improvements are necessary.

The Analyze phase uses a bar chart to visualize the several types of product defects. This helps identify which defect type occurs most frequently and should be prioritized for further investigation. In the Improve phase, the focus is on the highest-priority defect type by applying Failure Mode and Effects Analysis (FMEA). FMEA is used to identify potential failure modes and assess their Risk Priority Number (RPN), considering the severity, occurrence, and detection of each failure [14]. Based on this analysis, the five highest RPN scores are selected to develop targeted recommendations for quality improvement. Although the DMAIC methodology includes a Control phase to sustain improvements through standardized procedures and monitoring, this research does not explicitly implement the Control phase. Even so, the FMEA-based recommendations are expected to support the company in implementing and sustaining future improvements.

3. Results and discussion

3.1. Define

This phase involves identifying production processes, identifying problems, and mapping key processes using a SIPOC diagram, as well as identifying CTQ (Critical to Quality) attributes.

3.1.1. SIPOC Diagram

Table 2 illustrates the SIPOC diagram for the plastic straw production process. The SIPOC diagram indicates that the production process begins with raw materials (plastic pellets, dyes, cardboard, and plastic wrapping) sourced from various suppliers. The materials undergo extrusion, cutting, and quality control (QC) sampling to ensure that their dimensions meet standards. A flexible manufacturing process creates a curve in the product, enhancing user comfort and overall experience. After wrapping and packing 20,000 units per carton, manual quality control detects defects before shipping them to the packaged beverage industry as the customer. Rejected products are recycled, demonstrating an effective quality control system and sustainable waste management practices. This process flow ensures both product quality and operational efficiency.

Table 2 SIPOC Diagram of PT. XYZ's Plastic Straws Production

Supplier	Input	Process	Output	Customer
• Plastic pellets distributor • Dye factory • Cardboard packaging factory • Plastic wrapping factory	• Plastic pellets • Dyes • Plastic wrapping • Cardboard packaging	Extrusion Process → Cutting Process → Flexible Manufacturing Process → Wrapping Process → Packaging Process	• Finished goods products • Rejected products	Packaged Beverage Industry

3.1.2. Critical to Quality (CTQ)

In the production of plastic straws at PT. XYZ, the packaged beverage industry, as the primary customer, expects to receive products that are entirely free from defects. The quality standard applied states that a product is only considered high quality if it does not contain even the most minor defect. As a result, the Critical to Quality (CTQ) aspect focuses on meeting the required product specifications and standards at every stage of the process. CTQ refers to any defect that may occur during the production process and can impact product quality or cause it to fail in meeting the specifications required by the company and its customers [13]. Based on the data, four types of defects have been identified, corresponding to four critical to quality (CTQs) in this study: extrusion, flexible manufacturing process, wrapping, and packing.

3.2. Measure

At this stage, quantitative data calculations are conducted, specifically Defects Per Opportunity (DPO) and Defects Per Million Opportunities (DPMO), to assess the condition of product quality within the company. Then, the calculation of the sigma value will be conducted in each period. Table 3 presents the calculation results for DPO, DPMO, and sigma levels in the production of plastic straws.

Based on the results in Table 3, the plastic straws production process conducted by PT. XYZ already has a good process capability (with an average sigma value of 4.3 and an average DPMO value of 2,558.08). According to the classification of achieving multiple sigma levels, the DPMO value is comparable to that of the industry in America [12]. However, quality improvement is necessary to achieve level 5 sigma or even level 6 sigma, so that PT. XYZ can compete with world-class industries and produce more competitive products in the international market. The sigma value represents a picture of process performance, with the lowest sigma value in the first period, corresponding to a DPMO value (describing the process capability) of 3,426.47, which translates to a sigma value of 4.20. In comparison, the highest DPMO value is in the twelfth period, 2.141,75, which corresponds to a sigma value of 4.36.

3.3. Analyze

Based on the data processing from the previous measure phase, it can be concluded that the obstacles or problems within the company are related to quality. The problems identified in the processing results are defects that occur during periods 1 to 12. The results of the calculation indicate that numerous defects still exist and must be addressed to achieve the company's desired goals. At this stage, an analysis of the types of defects that occur most frequently is conducted using a bar chart, and an analysis of the causes of these defects is performed using a Fishbone diagram.

3.3.1. Bar Chart

Figure 1 presents the proportion of defects that occurred on each process of the plastic straws. It reveals that defects occur in four key production processes for plastic straws: wrapping, extrusion, packing, and flexible manufacturing. Among these, the wrapping process produces the highest total defects, accounting for 35.75% of the total, followed by extrusion (27.95%) and packing (23.84%). A flexible manufacturing process produces the fewest defects, with a defect rate of 12.46%. The high occurrence of defects in the wrapping process suggests that the wrapping process is the most critical-to-quality (CTQ) factor affecting product quality. While other types of defects are also present, their proportions are significantly lower in comparison. Therefore, the wrapping process will be the primary focus for further investigation. To determine the root causes of these wrapping defects, a detailed analysis will be conducted using a Fishbone Diagram (also known as an Ishikawa Diagram). This tool will help categorize potential contributing factors to support targeted corrective actions during the improvement phase [15].

Table 3 DPO, DPMO, and Sigma Calculation Result

Period	Production Quantity	Total Defect	CTQ	DPO	DPMO	Sigma
1	17,089.00	234.00	4.00	0.003	3,426.47	4.20
2	15,000.00	132.00	4.00	0.002	2,207.54	4.35
3	16,678.00	163.00	4.00	0.002	2,437.15	4.32
4	18,060.00	176.00	4.00	0.002	2,439.67	4.32
5	18,560.00	193.00	4.00	0.003	2,600.30	4.29
6	17,897.00	188.00	4.00	0.003	2,626.62	4.29
7	16,874.00	147.00	4.00	0.002	2,182.71	4.35
8	16,740.00	160.00	4.00	0.002	2,383.83	4.32
9	15,456.00	167.00	4.00	0.003	2,698.62	4.28
10	15,876.00	164.00	4.00	0.003	2,583.38	4.30
11	17,567.00	209.00	4.00	0.003	2,968.97	4.25
12	17,542.00	150.00	4.00	0.002	2,141.75	4.36
Average					2,558.08	4.30

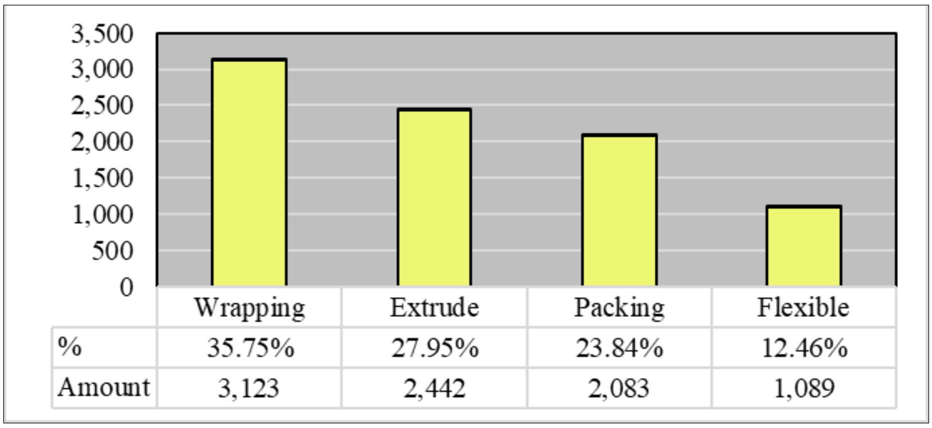

Figure 1 Total Defects on Plastic Straws Production

3.3.2. Fishbone Diagram

A detailed analysis of the causes of defects using the Fishbone tool focuses on the types of defects with the highest percentage, specifically those in the wrapping process, which are attributed to factors such as man, machine, material, method, and environment. This is illustrated in Figure 2. The root causes identified in the Fishbone Diagram serve as input for conducting an analysis using the FMEA (Failure Mode and Effects Analysis) method to evaluate potential causes. Subsequently, appropriate recommendations will be proposed during the Improve phase.

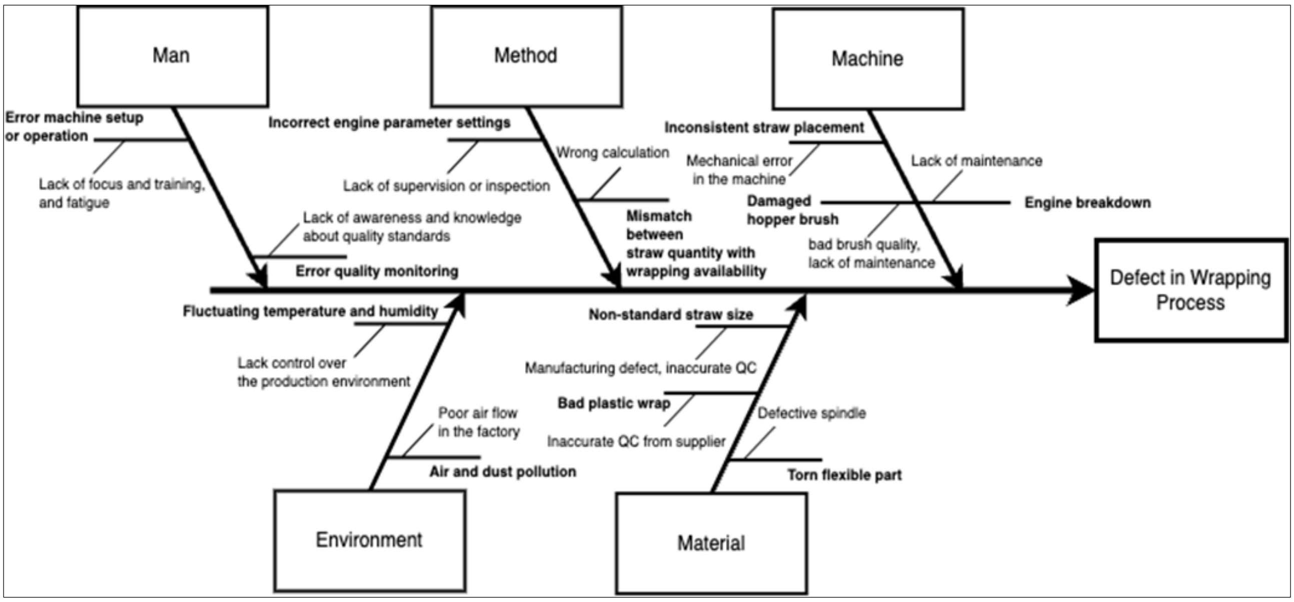

Figure 2 Fishbone Diagram of Defects on Wrapping Process

3.4. Improve

At this stage, an analysis will be conducted using FMEA, which aims to determine the severity, occurrence, and detection value of all identified defects. Based on all identified root causes from the Fishbone diagram, FMEA is conducted and sorted from the highest RPN to the lowest score. The proposed recommendations for improvement are based on priority, selecting the top five highest RPN scores, as shown in Table 4, which represent the highest risks that must be mitigated first. It also presents the detailed FMEA analysis of the five root causes with the highest RPNs, as identified through the fishbone diagram analysis.

Table 4 The Five Highest RPNs of FMEA Analysis Result

Process	Potential Failure Mode	Potential Effect	S	Potential Causes	O	Control	D	RPN	Improvement
Wrapping	Bad Plastic Wrap	Sealing is not optimal	7	Inaccurate QC from suppliers	6	Visual inspection of plastic wrapping	7	294	Conduct regular supplier audits to ensure that QC processes meet established standards
	Engine breakdown	Production downtime	9	Lack of Maintenance	4	Machine condition check	7	252	Perform regular preventive maintenance
	Error quality monitoring	Defects are not detected early	8	Lack of awareness and knowledge of quality standards	4	Field Supervision	7	224	Including quality aspects in performance appraisals to encourage awareness and concern for quality
	Damaged hopper brush	Disruption in the product manufacturing process	7	Bad brush quality, lack of maintenance	5	Field Supervision	6	210	Replace the hopper brush periodically according to the maintenance schedule
	Error machine setup or operation	Improper packaging	7	Lack of focus on operators	5	Field Supervision	5	175	Conduct inspection by supervisor before production starts

4. Conclusion

This study demonstrates the effective application of the Six Sigma DMAIC methodology in identifying and addressing quality issues in the plastic straw production process at PT XYZ. The analysis revealed that the wrapping process contributed the highest percentage of product defects, making it the most critical area for quality improvement. With an average sigma level of 4.3 and a DPMO of 2,558.084, the process exhibits moderate capability but still falls short of world-class standards. Using Fishbone Diagram and FMEA, the root causes of the defects were systematically identified and prioritized, resulting in actionable recommendations focused on supplier quality, machine maintenance, operator training, and component reliability. Although the Control phase was not fully implemented, the proposed improvements provide a strategic foundation for sustaining future quality gains.

Recommendations

The summary of recommendations for improvement is as follows

- Conduct regular supplier audits to ensure that quality control (QC) processes meet established standards.
- Perform regular preventive maintenance
- Including quality aspects in performance appraisals to encourage awareness and concern for quality
- Replace the hopper brush periodically, as outlined in the maintenance schedule
- Inspect by the supervisor before production starts

The findings highlight that Six Sigma tools effectively identify critical quality problems and propose targeted improvement strategies. The proposed strategy in the research can also serve as a benchmark for continuous improvement in the production process at PT. XYZ or other similar manufacturing settings.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict-of-interest to be disclosed.

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