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Analysis of Hard Box Product Failures Using Failure Mode and Effects Analysis (FMEA) and DMAIC Methods at PT XYZ

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Abstract

PT XYZ is a manufacturing company in the packaging industry that produces hard box products with high precision requirements. Based on production data from January to December 2025, the defect rate reached an average of 3.39% with a maximum value of 6.80%, exceeding the company standard of 3%, indicating that the production process is not yet fully under control and requires systematic quality improvement. This study aims to identify dominant defect types, analyze the root causes of failures, and determine effective improvement priorities. The method used is the DMAIC (Define, Measure, Analyze, Improve, Control) approach integrated with Failure Mode and Effect Analysis (FMEA) to assess failure risks based on the Risk Priority Number (RPN). The results show that the dominant defects are dimensional inaccuracy (22.91%), glue contamination (20.76%), and dented/damaged products (18.82%), contributing 62.49% of the total defects. Based on FMEA analysis, glue contamination has the highest RPN value of 384, making it the top priority for improvement. The main causes of defects are related to human factors, machine conditions, and unstandardized work methods. The proposed improvements include process standardization, development of standard operating procedures (SOP), use of supporting tools, enhancement of operator competence, and regular machine maintenance and calibration. The integration of FMEA within the DMAIC framework provides a more systematic and structured analytical approach and is projected to reduce the defect rate to meet or approach the company's quality standard.

Introduction

In the era of modern manufacturing industries, product quality has become a primary factor determining a company's success in maintaining competitiveness. Quality is no longer merely an additional attribute, but rather a fundamental requirement that must be fulfilled to maintain customer satisfaction and business sustainability (Montgomery, 2020; Amerta & Madhavi, 2023; Preziosi et al., 2022; Tahir et al., 2024). This is increasingly relevant in the packaging industry, which continues to grow alongside the rising demand from the e-commerce and premium product sectors (Aruan et al., 2023; Feber et al., 2020; Clement & Spinler, 2025; Kannan et l., 2024; Arora et al., 2023; García-Arca et al., 2025).

Hard box products are premium packaging products that require high dimensional precision and visual quality. The complexity of the production process increases the potential for product nonconformities (Glevitzky et al., 2025; Andersson et al., 2025; Ulewicz et al., 2023). Variations in the production process, such as material inconsistency, machine performance, and operator skills, can become the main sources of defects (Montgomery, 2020; Kohser et al., 2024; Hama Kareem et al., 2022). A high defect rate in the production process can directly impact increased operational costs and decreased production efficiency (Nashruddin, 2024; Fragapane et al., 2023; Chukwunweike et al., 2024; Ghelani et al., 2022; Chakraborty et al., 2024).

Based on observations at PT XYZ, the defect rate of hard box products shows unstable conditions. Data from the January–December 2025 period indicate an average defect rate of 3.39%, with the highest value reaching 6.80%, exceeding the company standard of 3%. This condition indicates that the production process has not operated optimally and that there are still uncontrolled process variations. In addition, the uneven distribution of defects at each production stage indicates the existence of critical processes that require further analysis (Blondheim, 2022; Cheng et al., 2026; Liu et al., 2024; Shah et al., 2023; Lin et al., 2022; Franco & Giovannini, 2023).

Various previous studies have applied the DMAIC approach to improve production process quality. This method is effective in identifying problems and systematically formulating improvements. However, the use of DMAIC without comprehensive risk analysis has not been able to determine improvement priorities in a specific and measurable manner. On the other hand, the Failure Mode and Effect Analysis (FMEA) method is capable of identifying potential failures and determining risk priorities based on the Risk Priority Number (RPN), but it is often used separately without integration into a systematic improvement framework (Al-Hourani & Hassanlou, 2025; Costa & Guarda, 2022; Mahmoudvand et al., 2025; Gonçalves et al., 2026; Chang et al., 2025).

Based on the literature review, most previous studies still used FMEA or DMAIC methods separately, with research objects limited to simple packaging such as corrugated boxes and cup packaging. Research specifically discussing the hard box industry in Indonesia remains limited, even though its production process is more complex and has a higher risk of failure. Most previous studies focused on other types of packaging such as duplex cartons, corrugated cartons, or cup packaging (Aruan et al., 2023; Kholisoh & Puspitasari, 2024; Riyanto & Munir, 2024). Therefore, this study integrates the Failure Mode and Effect Analysis (FMEA) method into the DMAIC framework to produce a more focused analysis in determining improvement priorities, which is expected to reduce defect rates and improve the quality of the hard box production process at PT XYZ.

Methods

Research Design

This research is analytical in nature and uses a case study approach focusing on the hard box production process at PT XYZ. The study focuses on identifying dominant defects, analyzing the root causes of defects, and developing improvement recommendations to enhance production quality. The case study approach was used because it allows an in-depth examination of quality problems that occur in a specific production setting. The DMAIC approach was selected because it provides a systematic quality improvement framework through the stages of define, measure, analyze, improve, and control. Through these stages, the research process can be carried out in a structured manner, starting from problem identification to the formulation of appropriate corrective actions. The FMEA method was applied to support the analyze stage by determining risk priorities based on the Risk Priority Number (RPN), so that the most critical causes of defects can be prioritized for improvement.

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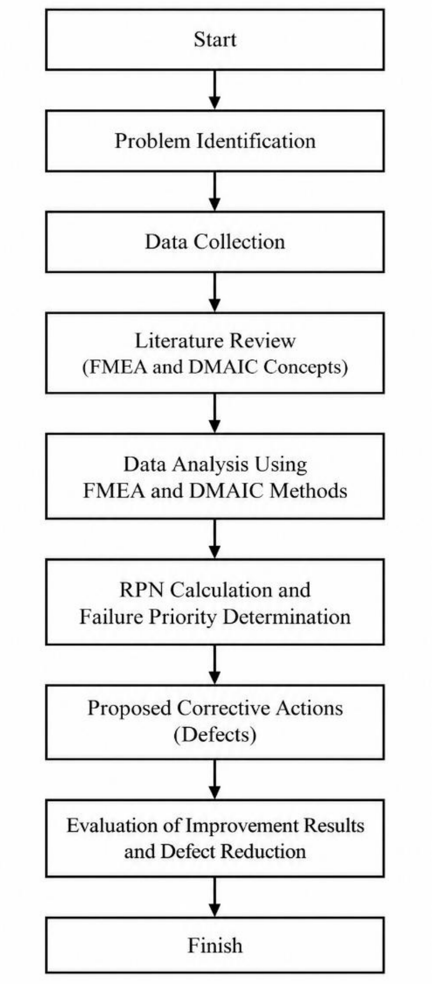

Figure 1. Research Flowchart

Research Object

The object of this study was the hard box production process at PT XYZ, which includes all production stages from material receiving to final product delivery. The production stages consist of material incoming, greyboard preparation, polar cutting, die-cutting, V-cutting, printing, laminating, assembly, wrapping & gluing, inspection, packing, and delivery. Each production stage has the potential to generate defects that may affect the final product quality.

Research Location and Time

This research was conducted at PT XYZ, a manufacturing company operating in the packaging industry, particularly hard box production. The research location was selected due to the existence of quality problems related to defect rates exceeding the company standard. The research was conducted from January to December 2025 using historical production and defect data during the specified period. In addition, direct observations and interviews were carried out to obtain information reflecting the actual production conditions.

Types and Sources of Data

The data used in this study consisted of primary and secondary data. Primary data were obtained directly through: 1) Direct observation of the hard box production process to identify potential defects at each production stage; 2) Interviews with production operators, quality control personnel, production leaders, and process engineers regarding the causes of defects and production conditions.

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Secondary data were obtained from company documents, including: 1) Production quantity data; 2) Defect quantity data; 3) Types of defects; 4) Production process data; 5) Company quality standards

Secondary data were used as the main basis for measuring defect levels and identifying dominant defects.

Data Collection Techniques

Data collection in this study was conducted using the following techniques:

Observation

Observation was carried out by directly monitoring the hard box production process at each production stage to understand the workflow and identify potential defects.

Interviews

Interviews were conducted with production operators, quality control supervisors, production leaders, and process engineers to obtain information regarding defect causes that could not be identified solely through numerical data.

Documentation

Documentation was conducted by collecting production records, defect reports, quality control reports, and other supporting company documents related to the hard box production process.

Data Processing and Analysis Techniques

Data processing and analysis were conducted using the DMAIC approach integrated with the FMEA method to provide a systematic and focused analysis for determining quality improvement priorities.

Define Stage

The define stage aimed to identify the main problems in the hard box production process. At this stage, the defect rate and dominant defect types were identified based on the company's historical production data.

Measure Stage

The measure stage aimed to evaluate production quality performance through: 1) Calculation of the number of defects; 2) Calculation of defect percentages; 3) Identification of dominant defects; 4) Analysis of production quality performance

The results of this stage were used to determine the actual condition of production quality and establish analysis priorities.

Analyze Stage

The analyze stage aimed to identify the root causes of defects using the following analytical tools:

Cause-and-Effect Diagram (Fishbone Diagram)

This method was used to identify defect causes based on categories such as manpower, machine, method, material, and environment.

Failure Mode and Effect Analysis (FMEA)

FMEA was used to determine the priority level of defect causes based on risk assessment parameters, including: a) Severity (S); b) Occurrence (O); c) Detection (D)

The Risk Priority Number (RPN) was calculated using the following equation:

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$$RPN = S \times O \times D$$

The assessment of Severity, Occurrence, and Detection values was conducted through discussions and interviews with personnel who understood the production process, namely the Quality Control Supervisor, Production Leader, and Process Engineer at PT XYZ using a 1–10 FMEA rating scale.

Improve Stage

The improve stage aimed to develop improvement recommendations based on defect causes with the highest RPN values. The proposed improvements focused on: 1) Work method improvement; 2) Production process standardization; 3) Increased quality supervision; 4) Operator training; 5) Periodic machine maintenance

This stage was limited to preparing improvement recommendations without direct implementation in the company.

Control Stage

The control stage aimed to develop quality control recommendations to maintain process stability after improvement initiatives. The recommended control measures included: 1) Development of Standard Operating Procedures (SOPs); 2) Periodic quality monitoring; 3) Routine production process evaluation; 4) Supervision of dominant defects

Data Analysis Technique

Data analysis was conducted using descriptive quantitative analysis by comparing production and defect data during the research period. The analysis results were used to evaluate production quality performance, identify dominant defects, determine root causes, and establish improvement priorities based on the highest RPN values. The descriptive quantitative approach was considered appropriate because the study focused on evaluating production quality performance rather than examining statistical relationships among variables.

Results and Discussion

Hard Box Assembly Process

The hard box production process at PT XYZ consists of several interconnected stages that influence the quality of the final product. Each stage has its own characteristics and different potential defects that may occur during the production process. The stages of the hard box production process are presented in Figure.

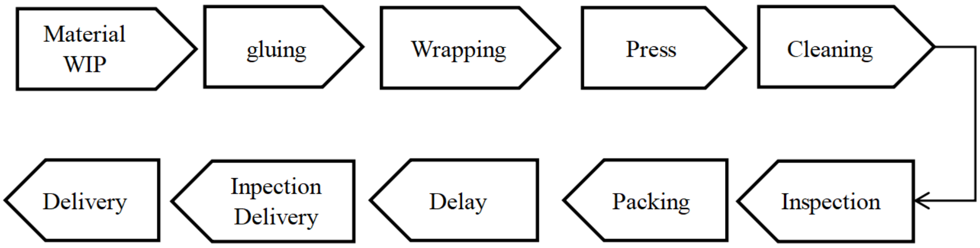

Figure. 2. Hard Box Production Process Flow

Based on Figure, the stages of the hard box production process at PT XYZ consists of five main stages, namely cutting, gluing, laminating, assembly, and finishing, where each stage has different characteristics and defect potentials. Defects may occur due to inaccurate cutting, improper glue application, laminating imperfections, assembly errors, and undetected defects during finishing. Therefore, operator accuracy, machine settings, and process control are essential factors in maintaining product quality. Since each stage contributes differently to defect occurrence, further analysis is necessary to identify the most dominant sources of defects and determine appropriate improvement actions to reduce defect rates and improve production quality.

Data Collection Results

Data collection in this study was conducted to obtain an overview of the actual conditions of the hard box production process at PT XYZ. The collected data consisted of primary and secondary data obtained through observations, interviews, and documentation from the production and quality control departments. The data included production quantity, defect quantity, and defect types during the January–December 2025 period. These data were used as the basis for analysis in the Measure stage to determine the defect level and identify dominant defects.

Table 1. Production and Defect Data per Month

Month	Total Production (pcs)	Glue Stain	Damaged/ Dented	Dimensional Inaccuracy	Air Bubble	Paper Wrinkle	Dent	Total Reject (pcs)	Reject Percentage
January	240,000	1,050	980	1,200	750	620	500	5,100	2.13%
February	228,000	1,000	900	1,150	700	600	450	4,800	2.10%
March	255,000	1,200	1,050	1,350	820	700	580	5,700	2.24%
April	248,000	1,350	1,200	1,500	950	820	680	6,500	2.62%
May	260,000	1,600	1,450	1,800	1,100	950	800	7,700	2.96%
June	270,000	1,850	1,700	2,100	1,300	1,100	950	9,000	3.33%
July	285,000	2,200	2,050	2,500	1,600	1,350	1,200	10,900	3.82%
August	290,000	2,600	2,400	2,900	1,900	1,600	1,500	12,900	4.45%
September	275,000	3,100	2,900	3,400	2,200	1,900	1,800	15,300	5.56%
October	250,000	3,500	3,200	3,800	2,500	2,200	1,800	17,000	6.80%
November	265,000	1,800	1,500	1,900	1,100	950	750	8,000	3.02%
December	280,000	900	750	850	500	420	380	3,800	1.36%
Total	**3,146,000**	**22,150**	**20,080**	**24,450**	**15,420**	**13,210**	**11,390**	**106,700**	—

Based on the collected data, it was found that the number of defects in the hard box production process fluctuated each month. This condition indicates that the production process was not yet fully stable and was still affected by process variations. Overall, the average defect rate of 3.39% remained above the company standard of 3%, indicating that further analysis was required to identify the root causes of defects and determine appropriate improvement priorities.

Production and Defect Data Analysis

Based on data obtained from the Quality Control Department of PT XYZ, production and defect data for hard box products during the January–December 2025 period are presented in Table . The results show that the defect rate fluctuated throughout the observation period, indicating inconsistency in the production process. The fluctuation suggests that the production system was still influenced by variations related to operators, working methods, machine conditions, and material handling. Although defect levels varied monthly, the overall average defect percentage remained above the company quality standard, indicating the need for continuous quality improvement efforts.

Analysis of Defect Types

The collected defect data were then classified based on defect type to identify the distribution and contribution of each defect during the research period. This classification aimed to simplify the identification of dominant defects that would become the focus of further analysis. Table presents the types of defects and their frequencies occurring during the production process.

Table 2. Defect Types and Frequencies

No	Defect Type	Code	Quantity (pcs)	Percentage (%)
1	Dimensional Inaccuracy	TP	24,450	22.91
2	Glue Stain	KL	22,150	20.76
3	Damaged/Dented	PR	20,080	18.82
4	Air Bubble	GB	15,420	14.45
5	Paper Wrinkle	KK	13,210	12.38
6	Dent	DT	11,390	10.67
Total			**106,700**	**100.00**

Based on Table 2, dimensional inaccuracy defects had the highest frequency, reaching 24,450 pcs or 22.91% of the total defects. This was followed by glue stain defects at 20.76% and damaged/dented defects at 18.82%. These three defect types contributed the largest proportion of total defects and can therefore be categorized as dominant defects. This finding indicates that the major quality problems in the hard box production process were associated with dimensional precision, gluing quality, and product handling during production.

The percentage of each defect type was calculated using the following formula:

$$\text{Defect Percentage} = \frac{\text{Number of Defects per Type}}{\text{Total Defects}} \times 100\%$$

The defect distribution analysis shows that improvement efforts should focus on dominant defects to achieve more effective and efficient quality improvement. Therefore, Pareto analysis was applied to identify priority defects requiring immediate corrective actions.

Pareto Analysis of Defects

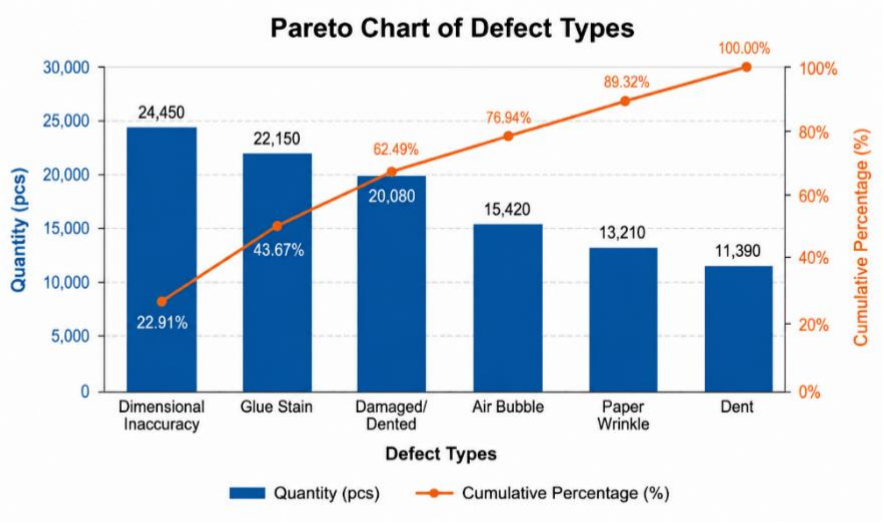

Figure 3. Pareto Analysis of Defects

Based on the Pareto diagram analysis, the majority of production quality problems were caused by several dominant defects, particularly dimensional inaccuracy, glue stains, and damaged/dented products. This result supports the Pareto principle, where a small number of defect types contributed to the majority of total defects occurring in the production process. Therefore, prioritizing corrective actions on these dominant defects is expected to significantly reduce the overall defect rate.

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Production Process and Defect Relationship Analysis

Based on the hard box production flow, each production stage has different defect potentials, ranging from gluing, wrapping, pressing, handling, to finishing processes. Each process possesses unique characteristics and risks that may affect final product quality. The relationship between production stages indicates that defects are not caused by a single factor but rather by the interaction of multiple production processes. Among all defect types, dimensional inaccuracy was identified as the most dominant defect with the highest frequency compared to other defects. This indicates that dimensional inaccuracy significantly affected product quality and should become the primary focus for improvement efforts. Based on direct observations on the production floor, the researcher mapped each production stage to the defect type most frequently occurring in that stage. The results are presented in Table 4.

Table 3. Mapping of Production Processes and Defect Types

No	Production Process	Defect Type	Quantity (pcs)	Percentage (%)
1	Wrapping	Dimensional Inaccuracy (TP)	24,450	22.91
2	Gluing	Glue Stain (KL)	22,150	20.76
3	Handling	Damaged/Dented (PR)	20,080	18.82
4	Pressing	Air Bubble (GB)	15,420	14.45
5	Pressing	Paper Wrinkle (KK)	13,210	12.38
6	Handling	Dent (DT)	11,390	10.67
Total			**106,700**	**100.00**

The mapping results indicate that dominant defects were distributed across several production stages, particularly wrapping, gluing, and handling processes. Dimensional inaccuracy defects occurring during the wrapping process had the highest contribution, accounting for 24,450 pcs or 22.91% of total defects. This was followed by glue stain defects during the gluing process at 20.76%, and damaged/dented defects during handling at 18.82%. In addition, air bubble and paper wrinkle defects occurring during the pressing process also contributed significantly to total defects. Meanwhile, dent defects during handling had the lowest contribution among all defect types.

These findings demonstrate that the wrapping, gluing, and handling processes are critical stages contributing significantly to production defects. Therefore, these stages should become the primary focus in the subsequent Failure Mode and Effect Analysis (FMEA) to determine the most critical defect causes and establish improvement priorities aimed at reducing defect rates and improving production quality.

Data Processing

Data processing in this study was carried out using the DMAIC (Define, Measure, Analyze, Improve, and Control) method integrated with the Failure Mode and Effect Analysis (FMEA) method. This approach was used to systematically identify quality problems, measure process performance, analyze the root causes of defects, and determine appropriate improvement priorities and recommendations.

Define

The Define stage was conducted to identify quality problems occurring in the hard box production process at PT XYZ. The identification process was based on production data and

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defective product data collected during the January–December 2025 period. Based on the collected data, it was found that the product defect rate still exceeded the company target, indicating the need for quality improvement efforts to reduce the number of defective products produced. Production data showed that the total hard box production during the research period reached 3,146,000 units, with a total of 106,700 defective products. The defect percentage reached 3.39%, while the maximum defect standard established by the company was 3%. This condition indicates that the production process had not yet achieved the company's quality target and therefore required further analysis to identify the causes of defects and determine appropriate corrective actions. The defect percentage was calculated using the following formula:

$$\text{Defect Percentage} = \frac{106{,}700}{3{,}146{,}000} \times 100\%$$

Based on the calculation results, the defect percentage obtained was 3.39%, indicating that the production process still experienced excessive defects compared to the company standard. This condition demonstrates that process variations and quality control issues were still present during production activities.

Furthermore, the identification of Critical to Quality (CTQ) characteristics was carried out to determine the quality attributes that most significantly affected the quality of hard box products. Based on observations and interviews with the production department, five main quality characteristics were identified as the company's primary concerns, namely: 1) Product dimensional accuracy; 2) Product surface cleanliness; 3) Adhesive bonding strength; 4) Product resistance to pressure; 5) Visual appearance neatness

These five Critical to Quality (CTQ) characteristics were used as the basis for measuring process capability and evaluating production quality performance during the Measure stage. The identification of CTQ characteristics also provided guidance in determining priority areas for quality improvement efforts in the hard box production process.

Measure

The Measure stage aims to determine the performance level of the hard box production process by measuring the defect level occurring during production activities. The measurements were conducted using defect rate, Defects Per Million Opportunities (DPMO), and sigma level calculations.

Determination of Critical to Quality (CTQ)

The determination of Critical to Quality (CTQ) characteristics was carried out based on the main quality attributes of hard box products that directly affect customer satisfaction. In this study, CTQ characteristics included product cleanliness, dimensional precision, adhesive strength, physical durability, and visual appearance quality. Table 4 presents the main quality characteristics that must be fulfilled by hard box products.

Table 4. Critical to Quality Characteristics of Hard Box Products

No	Quality Characteristics	Acceptable Standard	Defect Type if Nonconforming	CTQ (Defect Opportunity)
1	Dimensional Precision	Dimensions according to specifications and not misaligned	Dimensional Inaccuracy	1
2	Surface Cleanliness	No glue stains or dirt	Glue Stain	1

3	Adhesive Strength	Strong adhesive bonding without separation	Loose Glue	1
4	Shape Durability	No dents or deformation	Damaged/Dented	1
5	Visual Appearance	Neat and scratch free surface	Scratch or Untidy Surface	1

Based on Table 4, there are five main quality characteristics that must be fulfilled in hard box products. These characteristics were used as defect opportunities in the calculation of DPMO and sigma level. Therefore, the total CTQ used in this study was five defect opportunities for each product unit.

Defect Percentage Calculation

The percentage of each defect type was calculated to determine the contribution of each defect to the total number of defects occurring during the research period. The formula used is as follows:

$$\text{Defect Percentage} = \frac{\text{Number of Defects per Type}}{\text{Total Defects}} \times 100\%$$

The calculation results for each defect type are presented as follows:

Dimensional Inaccuracy (TP)

$$\frac{24{,}450}{106{,}700} \times 100\% = 22.91\%$$

Glue Stain (KL)

$$\frac{22{,}150}{106{,}700} \times 100\% = 20.76\%$$

Damaged/Dented (PR)

$$\frac{20{,}080}{106{,}700} \times 100\% = 18.82\%$$

Air Bubble (GB)

$$\frac{15{,}420}{106{,}700} \times 100\% = 14.45\%$$

Paper Wrinkle (KK)

$$\frac{13{,}210}{106{,}700} \times 100\% = 12.38\%$$

Dent (DT)

$$\frac{11{,}390}{106{,}700} \times 100\% = 10.67\%$$

The results indicate that the three dominant defects, namely dimensional inaccuracy, glue stain, and damaged/dented defects, contributed a cumulative percentage of:

$$22.91\% + 20.76\% + 18.82\% = 62.49\%$$

This finding shows that most quality problems were concentrated in a few major defect categories.

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Defect Rate Calculation

Defect rate was calculated to determine the percentage of defective products compared to total production. The formula used is as follows:

$$\text{Defect Rate} = \frac{\text{Number of Defects}}{\text{Total Production}} \times 100\%$$

Known data:

Total defects = 106,700 pcs

Total production = 3,146,000 pcs

The calculation result is:

$$\frac{106{,}700}{3{,}146{,}000} \times 100\% = 3.39\%$$

Based on the calculation, the hard box production defect rate was 3.39%, which exceeded the company standard of 3%. This result indicates that the production process still generated a significant number of nonconforming products and therefore required improvement efforts to reduce the defect rate.

Defects Per Million Opportunities (DPMO)

Defects Per Million Opportunities (DPMO) was used to measure the number of defects occurring in one million defect opportunities. DPMO provides a more accurate representation of process quality performance because it considers the number of defect opportunities in each product unit.

The DPMO formula is as follows:

$$DPMO = \frac{\text{Number of Defects}}{\text{Total Production} \times \text{CTQ}} \times 1{,}000{,}000$$

Known data:

Total defects = 106,700

Total production = 3,146,000

Total CTQ = 5

The calculation result is:

$$\frac{106{,}700}{3{,}146{,}000 \times 5} \times 1{,}000{,}000 = 6{,}783$$

Based on the calculation, the DPMO value obtained was 6,783 with a sigma level of 3.97 sigma. This result indicates that the hard box production process capability was within the average category of Indonesian manufacturing industries. Although the production process was generally capable of producing products according to specifications, process variations remained relatively high, causing defect levels to exceed the company target.

Sigma Level Calculation

The sigma level was calculated to determine process capability based on the obtained DPMO value. The higher the sigma level, the better the process capability in producing products according to specifications.

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Table 5. Sigma Level Conversion Results

Sigma Level	DPMO
3.80 Sigma	10,724
3.90 Sigma	8,232
3.97 Sigma	6,783
4.00 Sigma	6,210
4.10 Sigma	4,661

Based on the calculation results, the DPMO value of 6,783 was equivalent to a sigma level of 3.97 sigma. A sigma level of 3.97 indicates that the production process capability was relatively good, although improvement opportunities still existed to reduce defects and improve product quality. Therefore, further analysis was required to identify the root causes of defects in the next stage.

Pareto Diagram Analysis of Defects

After measuring process capability through defect rate, DPMO, and sigma level calculations, the next step was to identify the most dominant defects occurring during the hard box production process. This identification aimed to determine the priority problems requiring further analysis in the Analyze stage. The frequency distribution of defects during the January–December 2025 period is presented in Table 6.

Table 6. Frequency Distribution of Hard Box Product Defects

No	Defect Type	Code	Quantity (pcs)	Percentage (%)	Cumulative (%)
1	Dimensional Inaccuracy	TP	24,450	22.91	22.91
2	Glue Stain	KL	22,150	20.76	43.67
3	Damaged/Dented	PR	20,080	18.82	62.49
4	Air Bubble	GB	15,420	14.45	76.94
5	Paper Wrinkle	KK	13,210	12.38	89.32
6	Dent	DT	11,390	10.68	100.00
Total			**106,700**	**100.00**	—

Based on Table 6, dimensional inaccuracy defects were identified as the most dominant defect type with a total of 24,450 pcs or 22.91% of total defects. Glue stain defects ranked second with 22,150 pcs or 20.76%, while damaged/dented defects ranked third with 20,080 pcs or 18.82%. Cumulatively, these three defect types contributed 62.49% of the total defects occurring during the research period. This condition indicates that most hard box quality problems originated from several dominant defect types, requiring further analysis to determine the most effective improvement priorities.

To determine defect handling priorities, the defect frequency data in Table = were further analyzed using a Pareto Diagram based on the 80/20 principle, which states that most problems are generally caused by a small number of dominant factors. By using the Pareto Diagram, the company can focus improvement resources on defect types contributing the most to total product defects, making corrective actions more effective and targeted.

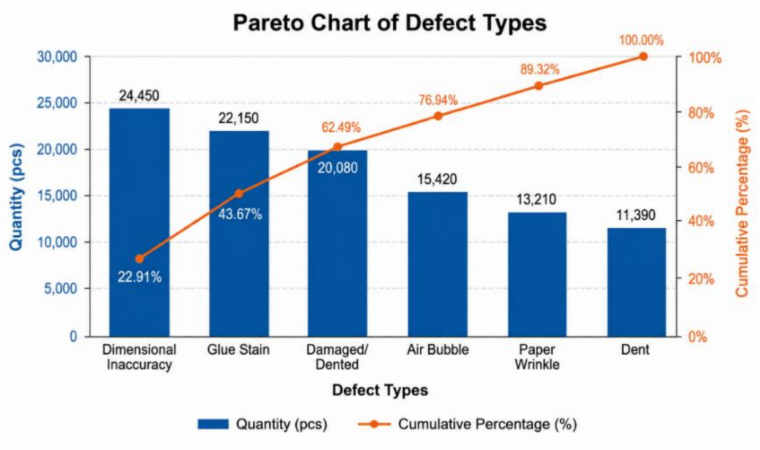

Figure 4. Pareto Diagram of Hard Box Product Defects

Based on Figure 4, dimensional inaccuracy, glue stain, and damaged/dented defects were identified as the three defect types with the largest contributions to total hard box defects. Collectively, these defects contributed 62.49% of all defects occurring during the research period. This result indicates that improvement efforts focused on these three defect types have the potential to provide the greatest impact on reducing the overall defect rate. Therefore, dimensional inaccuracy, glue stain, and damaged/dented defects were established as the main priorities for further analysis in the Analyze stage using fishbone diagrams and Failure Mode and Effect Analysis (FMEA) to identify root causes and determine appropriate corrective actions.

Analyze

The Analyze stage aims to identify the root causes of defects that become the priority for improvement based on the Pareto Diagram results obtained in the Measure stage. Based on the Pareto analysis, dimensional inaccuracy, glue stain, and damaged/dented defects were identified as the three defect types contributing the largest proportion of total hard box product defects, with a cumulative percentage of 62.49%. Therefore, these three dominant defects were further analyzed using Fishbone Diagrams to identify root causes and the Failure Mode and Effect Analysis (FMEA) method to determine improvement priorities.

Root Cause Analysis Using Fishbone Diagram

Based on field observations, interviews with production supervisors and quality control personnel, and a detailed evaluation of the hard box production process, several potential root causes were identified as contributing factors to dimensional inaccuracy, glue stains, and damaged or dented defects. The analysis was conducted to understand not only the visible defects found in the final product but also the underlying factors that occurred during each stage of production, from material preparation, forming, gluing, pressing, handling, to final inspection. The results of the investigation indicate that these defects are not caused by a single factor, but rather by a combination of human, technical, procedural, material, measurement, and environmental issues.

To provide a structured analysis, the causes were classified using the 5M+1E approach, consisting of Man, Machine, Method, Material, Measurement, and Environment. The Man factor refers to operator skills, work discipline, accuracy, and consistency in following production standards. The Machine factor includes machine condition, equipment calibration, glue application tools, and pressing performance. The Method factor relates to the clarity and implementation of standard operating procedures, work instructions, and process control during production. The Material factor includes the quality of paperboard, glue characteristics, and material handling before and during production. The Measurement factor concerns the accuracy of measuring tools, inspection methods, and quality control frequency. Meanwhile, the Environment factor includes workplace cleanliness, humidity, temperature, storage conditions, and the overall production layout.

By grouping the causes into these categories, the Fishbone Diagram helps identify the relationship between each defect and its possible sources. This analysis provides a clearer understanding of how dimensional inaccuracy may be related to inaccurate cutting, improper machine settings, or inconsistent measurement practices; how glue stains may result from excessive glue application, operator handling errors, or unsuitable glue viscosity; and how damaged or dented products may be caused by improper handling, poor storage conditions, or inadequate protection during the production process. The relationship between the identified defects and their root causes is illustrated in the Fishbone Diagram shown in Figure.

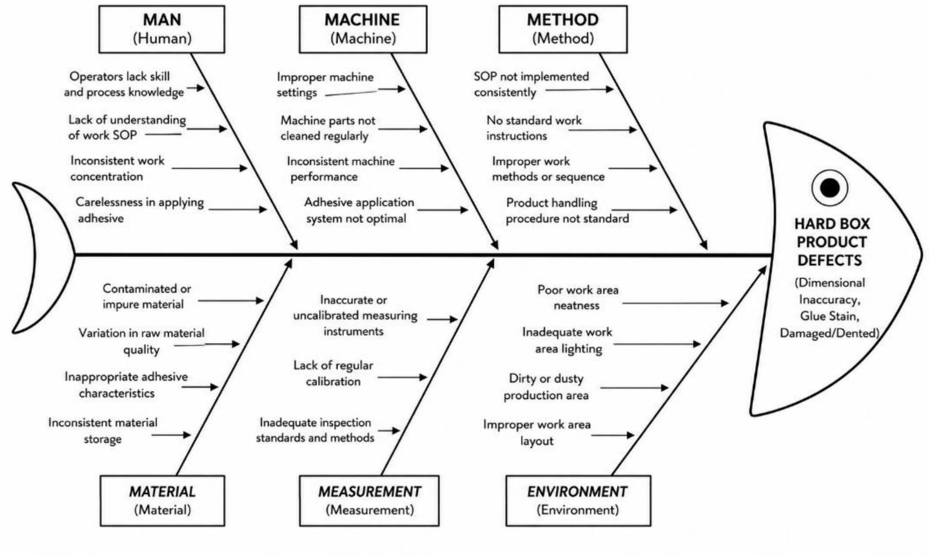

Figure 5. Fishbone Diagram of Hard Box Product Defects at PT XYZ

Based on the Fishbone Diagram and FMEA analysis, human and method factors were found to have the highest risk contribution to glue stain defects. This was indicated by higher Risk Priority Number (RPN) values compared to other factors, making them the main priorities for improvement. From the method aspect, it was found that Standard Operating Procedures (SOPs) had not been implemented consistently and no visual quality standards were available as references for operators. Material factors also contributed due to variations in raw material quality and changes in adhesive viscosity during the production process. Meanwhile, measurement and environmental aspects revealed weaknesses in quality inspection systems, inadequate lighting conditions, and improper product storage that potentially caused physical damage to hard box products.

Table 7. Relationship Between Fishbone Factors and FMEA

Factor	Cause	Failure Mode	RPN
Man	Lack of operator accuracy	Glue Stain	384
Method	No standardized SOP	Glue Stain	336
Machine	Unstable glue pressure	Glue Stain	288
Material	Adhesive viscosity changes	Glue Stain	252
Measurement	Inaccurate measuring instruments	Dimensional Inaccuracy	224
Environment	Dusty production area	Glue Stain	196

Based on these findings, it can be concluded that defects were not caused by a single factor, but rather by a combination of multiple factors occurring throughout the production process. Therefore, further analysis using Failure Mode and Effect Analysis (FMEA) was required to determine the risk priority level of each identified cause and identify the most effective corrective actions.

Failure Mode and Effect Analysis (FMEA)

After identifying the root causes of defects using the Fishbone Diagram, the next step was conducting Failure Mode and Effect Analysis (FMEA). The FMEA method was used to determine the risk level of each defect type occurring in the hard box production process. The assessment was conducted based on three parameters, namely Severity (S), Occurrence (O), and Detection (D). These parameters were then used to calculate the Risk Priority Number (RPN) as the basis for determining improvement priorities.

Severity (S) Rating Scale

Severity represents the level of impact caused by a defect on product quality and customer satisfaction.

Table 8. Severity Rating Criteria for Failure Modes in Hard Box Product Production

Score	Criteria	Impact on Hard Box Products
10	Extremely Hazardous	Product cannot be used at all
8–9	High	Product function is disturbed and customers will complain
6–7	Moderate	Product aesthetics are disturbed and customers may complain
4–5	Low	Minor defects and customers rarely complain
1–3	Very Low	Defects are barely detected by customers

Occurrence (O) Rating Scale

Occurrence represents the frequency of defect occurrence during production.

Table 9. Occurrence Rating Criteria for Failure Modes in Hard Box Product Production

Score	Criteria	Frequency of Occurrence
10	Very Frequent	>10% of total production
8–9	Frequent	5%–10% of total production
6–7	Moderate	1%–5% of total production
4–5	Low	0.1%–1% of total production
1–3	Very Low	<0.1% of total production

Detection (D) Rating Scale

Detection represents the capability of the inspection system to identify defects before products reach customers.

Table 10. Detection Rating Criteria for Failure Modes in Hard Box Product Production

Score	Criteria	Detection Capability
10	Almost Impossible	No inspection system available
8–9	Very Difficult	Visual inspection without supporting tools
6–7	Moderate	Visual inspection using checklists
4–5	Fairly Easy	Inspection using sampling measurement tools
1–3	Very Easy	100% inspection using automatic tools

The assessment of Severity (S), Occurrence (O), and Detection (D) values was conducted through discussions and interviews with personnel who understood the production process, namely the Quality Control Supervisor, Production Leader, and Process Engineer of PT XYZ. The final scores were determined based on consensus assessment among respondents.

The Risk Priority Number (RPN) formula is as follows:

$$RPN = S \times O \times D$$

The higher the RPN value, the greater the risk level caused by the defect, and therefore the higher the priority for corrective action.

Table 11. FMEA Results for Each Defect Type

No	Defect Type	Code	Severity (S)	Occurrence (O)	Detection (D)	RPN	Priority
1	Glue Stain	KL	8	8	6	384	1
2	Damaged/Dented	PR	7	7	6	294	2
3	Dimensional Inaccuracy	TP	8	7	5	280	3
4	Air Bubble	GB	6	6	5	180	4
5	Paper Wrinkle	KK	5	6	5	150	5
6	Dent	DT	5	5	5	125	6

Based on the FMEA analysis results, glue stain defects had the highest RPN value of 384. This result indicates that glue stain defects had the highest risk level compared to other defect types because they had high severity, frequent occurrence, and limited detection capability. Damaged/dented defects ranked second with an RPN value of 294, while dimensional inaccuracy defects ranked third with an RPN value of 280. These three defect types were also identified as dominant defects in the previous Pareto analysis and therefore became the main focus for improvement planning. Meanwhile, air bubble, paper wrinkle, and dent defects had relatively lower RPN values and could be addressed after the main priority defects were improved. The determination of improvement priorities in this study was based on the Risk Priority Number (RPN). The higher the RPN value, the greater the risk caused by the defect and the higher the priority for corrective action.

Risk Priority Number (RPN) Calculation

The Risk Priority Number (RPN) calculation was performed by multiplying the values of Severity (S), Occurrence (O), and Detection (D) for each defect type. The RPN value was used to determine the priority level of risks that must be handled by the company.

Example of RPN Calculations

Glue Stain Defect

$$RPN = 8 \times 8 \times 6 = 384$$

Damaged/Dented Defect

$$RPN = 7 \times 7 \times 6 = 294$$

Dimensional Inaccuracy Defect

$$RPN = 8 \times 7 \times 5 = 280$$

Air Bubble Defect

$$RPN = 6 \times 6 \times 5 = 180$$

Paper Wrinkle Defect

$$RPN = 5 \times 6 \times 5 = 150$$

Dent Defect

$$RPN = 5 \times 5 \times 5 = 125$$

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Based on the RPN calculation results, glue stain defects had the highest RPN value of 384, indicating that this defect type posed the highest risk and therefore should become the primary priority for corrective action. Damaged/dented defects and dimensional inaccuracy defects followed with RPN values of 294 and 280 respectively. These three defect types contributed the largest proportion of total hard box product defects and therefore became the main focus in developing improvement recommendations during the Improve stage. Meanwhile, air bubble, paper wrinkle, and dent defects had lower RPN values of 180, 150, and 125 respectively. However, these defects still required proper control to maintain product quality consistency and prevent increased defect levels in future production periods.

Improve

The Improve stage was conducted to provide corrective action recommendations for the factors causing defects with the highest risk values based on the FMEA analysis results. The proposed improvements focused on reducing defect levels through improvements in work methods, machine control, material quality, and operator accuracy during the production process.

Based on the FMEA analysis, the defects with the highest Risk Priority Number (RPN) values were primarily caused by human factors, work methods, and machine conditions. Therefore, the proposed corrective actions were focused on these factors to reduce the possibility of defects occurring during the hard box production process. The recommended improvement plans are presented in Table 10.

Table 12. Improvement Plans for Priority Defects

No	Defect Type	RPN Value	Main Root Cause	Proposed Corrective Actions
1	Glue Stain	384	Inconsistent adhesive application, lack of operator accuracy, and suboptimal adhesive application tools	Develop adhesive usage standards, provide operator training on adhesive application techniques, conduct regular inspection and maintenance of adhesive application tools, and provide visual quality standards as inspection references.
2	Damaged/Dented	294	Improper product handling and disorganized product storage	Provide product handling training for operators, improve storage area layout, establish maximum stacking limits, and increase supervision during product transfer and storage.
3	Dimensional Inaccuracy	280	Unstable machine settings, operator inaccuracy, and inadequate dimensional inspection	Conduct periodic machine calibration and inspection, increase the frequency of dimensional inspections, provide operator training, and improve supervision of SOP implementation during production.
4	Air Bubble	180	Inconsistent material quality and unstable process parameters	Improve raw material quality inspection before use, adjust process parameters according to standards, and strengthen

				supervision during production processes.
5	Paper Wrinkle	150	Poor material condition and inconsistent work methods	Conduct material condition inspection before production, consistently implement SOPs, and improve supervision during the paper laminating process.
6	Dent	125	Product collision during transfer and storage	Increase operator caution during product handling, improve storage methods, and conduct periodic inspections of finished product storage areas.

Based on Table, the main improvement priorities were focused on glue stain, damaged/dented, and dimensional inaccuracy defects because these defects had the highest RPN values compared to other defect types. These three defects were also identified as dominant defects in the Pareto analysis and therefore had the greatest potential impact on reducing the total number of hard box product defects. Glue stain defects became the highest priority because they were mainly caused by inconsistent adhesive application and inadequate operator accuracy. Therefore, standardization of adhesive application methods, operator training, and routine maintenance of adhesive application tools were considered essential to improve process consistency and product cleanliness. Damaged/dented defects were primarily caused by improper product handling and inadequate storage systems. Improvement efforts focused on enhancing operator awareness regarding handling procedures, optimizing storage layouts, and increasing supervision during product movement and storage activities to minimize physical damage to products.

Meanwhile, dimensional inaccuracy defects were related to unstable machine settings, insufficient dimensional inspections, and operator inaccuracies during production. Corrective actions were therefore directed toward machine calibration, stricter dimensional inspection procedures, and operator competency improvement through training and SOP supervision. Although air bubble, paper wrinkle, and dent defects had lower RPN values, these defects still required preventive and corrective control actions to maintain process stability and prevent increases in defect levels during future production periods. Consistent implementation of the proposed improvement plans is expected to minimize the root causes of defects and continuously improve the quality performance of hard box products at PT XYZ.

Control

The Control stage is the final phase of the DMAIC method, which aims to ensure that the proposed improvement actions can be implemented consistently and sustainably. This stage was carried out through the preparation of a control plan as a guideline for the company in monitoring the production process and preventing the recurrence of defects that had become improvement priorities.

The control plan was focused on glue stain, damaged/dented, and dimensional inaccuracy defects because these three defect types had the highest Risk Priority Number (RPN) values and contributed the largest proportion of total hard box product defects. Through a structured control system, the company is expected to maintain production process quality and reduce the possibility of defects occurring in future production periods.

Table presents the control plan prepared as a preventive and monitoring measure to ensure that the proposed improvements can be implemented consistently so that hard box product quality can be maintained and defect levels minimized.

Table 13. Quality Control Activities for Defect Prevention in Hard Box Product Production

No	Defect Type	Control Activities	Frequency	Person in Charge
1	Glue Stain	Inspection of adhesive usage according to standards and checking the condition of adhesive application tools	Every beginning and end of shift	Operators and Production Supervisors
2	Glue Stain	Visual inspection of adhesive application results on products	Every production process	Quality Control
3	Damaged/Dented	Monitoring of product handling and storage processes	Daily	Production Supervisor
4	Damaged/Dented	Inspection of storage area conditions and product stacking	Weekly	Warehouse Supervisor
5	Dimensional Inaccuracy	Calibration and inspection of production machine settings	Monthly	Maintenance Technician
6	Dimensional Inaccuracy	Product dimensional inspection using standard measuring instruments	Every production batch	Quality Control
7	All Defects	Evaluation of defect levels and implementation of quality briefing	Monthly	Production Manager and Quality Control

Based on Table 11, the control activities were carried out through inspections, production process monitoring, machine calibration, and periodic quality evaluations. These activities were designed to ensure that the factors causing defects could be controlled and would not generate the same quality problems repeatedly. In addition, the involvement of operators, production supervisors, quality control personnel, and maintenance technicians plays an important role in the successful implementation of sustainable quality control. The active participation of each responsible department is expected to improve coordination and strengthen compliance with the company's Standard Operating Procedures (SOPs). Through the implementation of a structured control plan, PT XYZ is expected to maintain production process stability, improve adherence to quality standards, and reduce the possibility of defects in hard box products. Consequently, product quality can be consistently maintained in accordance with the standards established by the company while supporting continuous quality improvement efforts in the production process.

This study aimed to identify the dominant defects in hard box products and develop improvement recommendations using the DMAIC and Failure Mode and Effect Analysis (FMEA) methods. Based on the production data analysis for the January–December 2025 period, total hard box production reached 3,146,000 units with a total defect quantity of 106,700 units, equivalent to 3.39% of total production. These findings indicate that the production process had not yet achieved the company's maximum defect standard of 3%, thereby requiring continuous quality improvement efforts.

The process capability analysis showed a Defects Per Million Opportunities (DPMO) value of 6,783 with a sigma level of 3.97 sigma. This result indicates that the production process was categorized as relatively good and consistent with the average quality capability of manufacturing industries in Indonesia. However, the sigma level also indicates that process variations still existed and contributed to the occurrence of defects exceeding the company target. According to (Montgomery, 2020) a higher sigma level reflects better process capability and lower process variation, whereas processes below the Six Sigma standard still require improvement to achieve higher quality consistency. Therefore, the obtained sigma level demonstrates that the production process at PT XYZ still has opportunities for quality improvement, particularly in controlling dominant defects.

The Pareto analysis revealed that dimensional inaccuracy, glue stain, and damaged/dented defects were the three dominant defect categories contributing 62.49% of the total hard box product defects. This finding supports the Pareto principle, which states that most quality problems are generally caused by a small number of dominant factors. Similar findings were reported by (Aruan et al., 2023) who found that a limited number of dominant defects significantly affected packaging product quality performance. In this study, dimensional inaccuracy defects were mainly associated with unstable machine settings and insufficient dimensional inspection, while glue stain defects were related to inconsistent adhesive application and inadequate operator accuracy. Damaged/dented defects were primarily caused by improper handling and inadequate storage systems.

The Fishbone Diagram analysis showed that defect causes originated from human, machine, method, material, measurement, and environmental factors. Human and method factors were identified as the main contributors to glue stain defects due to inconsistent SOP implementation and operator inaccuracies during adhesive application. According to Heizer (2016) human error and lack of process standardization are among the most common causes of quality deviations in manufacturing industries. Furthermore, material quality inconsistency and unstable machine performance also contributed significantly to production defects (Antosz et al., 2024; Bono et al., 2023; Ismail et al., 2022). These findings indicate that production quality problems in the hard box industry are multidimensional and cannot be attributed to a single factor.

The FMEA analysis further demonstrated that glue stain defects had the highest Risk Priority Number (RPN) value of 384, followed by damaged/dented defects with an RPN value of 294 and dimensional inaccuracy defects with an RPN value of 280. The high RPN value of glue stain defects indicates that this defect type has a high severity level, occurs relatively frequently, and is still difficult to detect consistently during inspection activities. According to (Stamatis, 2003) defects with high RPN values should become the primary focus of corrective actions because they pose the greatest risk to product quality and customer satisfaction. Therefore, the proposed improvement actions focused on standardizing adhesive application methods, improving operator skills, conducting periodic machine calibration, strengthening quality inspection systems, and improving product handling and storage systems.

The comparison with previous studies was conducted to identify similarities and differences between this study and previous research related to quality control using Six Sigma, DMAIC, and FMEA methods. Several previous studies showed that the application of Six Sigma-based approaches was effective in identifying dominant defects and determining appropriate corrective actions in manufacturing industries. Research conducted by (Waruwu et al., 2022) on paper products found that wrinkle and wavy defects were dominant defects, and the proposed improvements focused on machine lubrication and sensor calibration. Similarly, (Aruan et al., 2023) identified ink stain defects as the dominant problem in duplex carton packaging production, with improvement efforts focusing on SOP implementation, preventive maintenance, and quality reporting systems. Meanwhile, (Yunian et al., 2024) reported that sewing defects in flour packaging products contributed 52.8% of total defects, with worker fatigue identified as the primary cause.

Compared to previous studies, this research specifically focused on hard box products, which have more complex production characteristics and higher risks of dimensional, adhesive, and physical appearance defects. In addition, this study integrated DMAIC stages with FMEA analysis to determine defect priorities based on Risk Priority Number (RPN) values. The results demonstrated that glue stain defects had the highest RPN value of 384 and therefore became the main priority for improvement actions. This finding provides an additional contribution to quality control studies in the packaging industry, particularly in hard box manufacturing processes that have not been extensively studied in previous research.

Based on the results of the Define, Measure, Analyze, Improve, and Control stages, several improvement recommendations were proposed to address the main causes of hard box product defects. These recommendations were developed based on the Pareto Diagram, Fishbone Diagram, and FMEA analysis results, which identified dimensional inaccuracy, glue stain, and damaged/dented defects as the dominant defects with the highest risk levels. Although this study did not directly implement the proposed improvements, a simulation analysis was conducted to estimate the potential impact of improvement implementation on reducing defect levels. The simulation was based on conservative assumptions regarding the effectiveness of improvement actions, including SOP standardization, operator training, preventive machine maintenance, enhanced production monitoring, and strengthened inspection systems. This simulation aimed to provide management with an overview of the potential quality improvement opportunities that could be achieved if the proposed corrective actions were implemented consistently.

The simulation results showed that glue stain defects could potentially decrease by 15%, while dimensional inaccuracy and damaged/dented defects could each decrease by 10%. Overall, the three dominant defects were projected to decrease by 7,776 units. Consequently, the total number of defects was projected to decrease from 106,700 units to 98,924 units. This reduction would decrease the defect rate from 3.39% to 3.14%.

The DPMO value after simulation was projected to decrease from 6,783 to 6,289, while the sigma level was projected to increase from 3.97 sigma to approximately 4.00 sigma. These findings indicate that focusing improvement efforts on dominant defects identified through Pareto and FMEA analysis has the potential to significantly improve production quality performance. According to (Pande et al., 2002) even small increases in sigma level can produce substantial reductions in defects and operational costs in manufacturing industries. Therefore, consistent implementation of the proposed corrective actions is expected to improve process capability and product quality sustainability at PT XYZ.

The results of this study demonstrate that the integration of DMAIC and FMEA methods is effective in systematically identifying dominant defects, analyzing root causes, determining improvement priorities, and estimating the potential impact of quality improvement actions. Thus, the research objectives of identifying defects, analyzing defect causes, and developing quality improvement recommendations for hard box production processes were successfully achieved

Conclusion

Based on the results of the research conducted using the DMAIC and Failure Mode and Effect Analysis (FMEA) methods, it can be concluded that the quality performance of the hard box production process at PT XYZ still requires improvement because the defect rate exceeded the company's quality standard. The analysis results showed that the average defect rate reached 3.39%, which was higher than the company target of 3%, indicating that the production process had not yet been fully controlled and still experienced process variations that affected product quality.

The study identified three dominant defect types, namely dimensional inaccuracy, glue stain, and damaged/dented defects, which collectively contributed 62.49% of the total defects occurring during the production period. These findings indicate that most production quality problems were concentrated in a few major defect categories that significantly influenced the overall quality performance of hard box products.

Furthermore, the FMEA analysis showed that glue stain defects had the highest Risk Priority Number (RPN) value of 384, followed by damaged/dented defects with an RPN value of 294 and dimensional inaccuracy defects with an RPN value of 280. The high RPN value of glue stain defects indicates that this defect has the highest level of risk and therefore should become the primary focus of corrective actions and quality improvement efforts.

The integration of the FMEA method into the DMAIC framework proved to provide a more systematic, structured, and objective approach in identifying dominant defects, analyzing root causes, and determining improvement priorities. Through this integrated approach, the study was able to identify the main factors causing defects, including human factors, machine conditions, work methods, and material quality, which collectively contributed to the occurrence of production defects.

Based on the analysis results, several improvement recommendations were proposed, including work process standardization, preparation and implementation of Standard Operating Procedures (SOPs), improvement of operator competencies through training, enhancement of quality inspection activities, use of supporting tools, and periodic machine maintenance. The implementation of these improvement actions is projected to reduce defect levels, improve process capability, and support the achievement of the company's quality standards consistently and sustainably.

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References

Al-Hourani, S., & Hassanlou, A. (2025). An enhanced RPN model incorporating maintainability complexity for risk-based maintenance planning in the pharmaceutical industry. *Processes*, *13*(10), 3153. https://doi.org/10.3390/pr13103153

Amerta, L., & Madhavi, I. (2023). Exploring service quality and customer satisfaction in the service industry: A mixed-methods analysis. *Journal on Economics, Management and Business Technology*, *2*(1), 1-16. https://doi.org/10.35335/jembut.v2i1.184

Andersson, M., Hvam, L., Forza, C., & Mortensen, N. H. (2025). The Impact of Product Variety on Quality Conformance in Continuous Process Manufacturing: A Quantitative Investigation in a Chemical Industry Context. *Applied Sciences*, *15*(21), 11618. https://doi.org/10.3390/app152111618

Antosz, K., Knapčíková, L., & Husár, J. (2024). Evaluation and Application of Machine Learning Techniques for Quality Improvement in Metal Product Manufacturing. *Applied Sciences*, *14*(22), 10450. https://doi.org/10.3390/app142210450

Arora, T., Chirla, S. R., Singla, N., & Gupta, L. (2023). Product packaging by e-commerce platforms: impact of covid-19 and proposal for circular model to reduce the demand of virgin packaging. *Circular Economy and Sustainability*, *3*(3), 1255-1273. https://doi.org/10.1007/s43615-022-00231-4

Aruan, R. P. P., Saryatmo, M. A., & Kristina, H. J. (2023). Usulan peningkatan kualitas produksi kemasan karton dupleks produk AA menggunakan metode Six Sigma dan seven new quality tools. *Jurnal Muara Sains, Teknologi, Kedokteran dan Ilmu Kesehatan, 7*(1), 21–32. https://doi.org/10.24912/jmstkik.v7i1.22781

Blondheim Jr, D. (2022). Improving manufacturing applications of machine learning by understanding defect classification and the critical error threshold. *International Journal of Metalcasting*, *16*(2), 502-520. https://doi.org/10.1007/s40962-021-00637-0

Bono, F. M., Radicioni, L., & Cinquemani, S. (2023). A novel approach for quality control of automated production lines working under highly inconsistent conditions. *Engineering applications of artificial intelligence*, *122*, 106149. https://doi.org/10.1016/j.engappai.2023.106149

Chakraborty, D., Yurdusen, A., Mouchaham, G., Nouar, F., & Serre, C. (2024). Large-scale production of metal–organic frameworks. *Advanced Functional Materials*, *34*(43), 2309089. https://doi.org/10.1002/adfm.202309089

Chang, J., Kim, H., Lalonde, R., Doraisamy, E., & Vargo, J. (2025). Fuzzy Analytical Hierarchy Process-based Risk Priority Number Approach in Failure Modes and Effects Analysis for Magnetic Resonance Imaging-guided High-dose-rate Brachytherapy for Gynecologic Cancer. *Advances in Radiation Oncology*, *10*(4), 101731. https://doi.org/10.1016/j.adro.2025.101731

Cheng, H., Husen, J. H., Lu, Y., Racharak, T., Yoshioka, N., Ubayashi, N., & Washizaki, H. (2026). Generative ai for requirements engineering: A systematic literature review. *Software: Practice and Experience*, *56*(2), 141-170. https://doi.org/10.1002/spe.70029

Chukwunweike, J., Anang, A. N., Adeniran, A. A., & Dike, J. (2024). Enhancing manufacturing efficiency and quality through automation and deep learning: addressing redundancy, defects, vibration analysis, and material strength optimization Vol. 23. *World Journal of Advanced Research and Reviews. GSC Online Press*, *23*. https://doi.org/10.30574/wjarr.2024.23.3.2800

Clement, L., & Spinler, S. (2025). From returns to re-usage: A data-driven strategy for sustainable packaging: A case study in e-commerce. *Journal of Cleaner Production, 510*, 145584.

Clement, L., & Spinler, S. (2025). From returns to re-usage: A data-driven strategy for sustainable packaging—A case study in e-commerce. *Journal of Cleaner Production*, *510*, 145584. https://doi.org/10.1016/j.jclepro.2025.145584

Costa, I., & Guarda, T. (2022, April). Information System Security Risk Priority Number: A New Method for Evaluating and Prioritization Security Risk in Information System Applying FMEA. In *Proceedings of International Conference on Information Technology and Applications: ICITA 2021* (pp. 561-572). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-16-7618-5_49

Feber, D., Lingqvist, O., & Nordigården, D. (2020). *How the packaging industry can navigate the coronavirus pandemic*. McKinsey & Company.

Fragapane, G., Eleftheriadis, R., Powell, D., & Antony, J. (2023). A global survey on the current state of practice in Zero Defect Manufacturing and its impact on production performance. *Computers in Industry*, *148*, 103879. https://doi.org/10.1016/j.compind.2023.103879

Franco, A., & Giovannini, C. (2023). Recent and future advances in water electrolysis for green hydrogen generation: Critical analysis and perspectives. *Sustainability*, *15*(24), 16917. https://doi.org/10.3390/su152416917

García-Arca, J., Garrido, A. T. G. P., Escurís-Ouviña, J., & Prado-Prado, J. C. (2025). Implementing a sustainable and efficient packaging system for e-commerce: An empirical perspective in the household sector. *Journal of Industrial Engineering and Management*, *18*(2), 245-266. https://doi.org/10.3926/jiem.8604

Ghelani, H. (2022). Automated Defect Detection in Printed Circuit Boards: Exploring the Impact of Convolutional Neural Networks on Quality Assurance and Environmental Sustainability in Manufacturing. *International Journal of Advanced Engineering Technologies and Innovations*, *1*(4), 275-289.

Glevitzky, M., Glevitzky, I., Mucea-Ștef, P., & Popa, M. (2025). The “Daily Challenge” Tool: A Practical Approach for Managing Non-Conformities in Industry. *Sustainability*, *17*(13), 5918. https://doi.org/10.3390/su17135918

Gonçalves, H. O., Amaral, R., & Pereira, J. C. (2026). A Hybrid FMEA-AHP Framework for Risk Prioritization in Nontransparent Artificial Intelligence Systems. *Risk Analysis*, *46*(7), e70297. https://doi.org/10.1111/risa.70297

Hama Kareem, J. A., Mohammed, B. I., & Abdulwahab, S. A. (2022). Optimal materials handling equipment and defective product reduction skills in enhance overall production efficiency. *Sage Open*, *12*(4), 21582440221128769. https://doi.org/10.1177/21582440221128769

Heizer, J. (2016). *Operations management* (11th ed.). Pearson Education India.

Ismail, M., Mostafa, N. A., & El-Assal, A. (2022). Quality monitoring in multistage manufacturing systems by using machine learning techniques. *Journal of intelligent manufacturing*, *33*(8), 2471-2486. https://doi.org/10.1007/s10845-021-01792-1

Kannan, S., Parashar, B., & Chaurasia, A. (2024). E-commerce and green packaging: Sustainable business trends. In *Green innovations for industrial development and business sustainability* (pp. 22–39). CRC Press.

Kholisoh, I. N., & Puspitasari, N. B. (2024). Mengetahui kualitas proses produksi *corrugated carton sheet* menggunakan metode FTA dan FMEA melalui fase DMAIC (Studi kasus: PT Jawasurya Kencana Indah Semarang). *Industrial Engineering Online Journal, 13*(2).

Kohser, R. A., Collins, P. C., & Black, J. T. (2024). *DeGarmo's materials and processes in manufacturing*. John Wiley & Sons.

Lin, H., Lin, J., & Wang, F. (2022). An innovative machine learning model for supply chain management. *Journal of Innovation & Knowledge*, *7*(4), 100276. https://doi.org/10.1016/j.jik.2022.100276

Liu, H., Yu, H., Guo, C., Chen, X., Zhong, S., Zhou, L., ... & Lu, J. (2024). Review on fatigue of additive manufactured metallic alloys: microstructure, performance, enhancement, and assessment methods. *Advanced Materials*, *36*(17), 2306570. https://doi.org/10.1002/adma.202306570

Mahmoudvand, R., Fiori Maccioni, A., Frigau, L., & Banks, D. (2025). Probability Distribution of Risk Priority Numbers in Failure Mode and Effects Analysis. *Risk Analysis*, *45*(12), 4783-4795. https://doi.org/10.1111/risa.70143

Montgomery, D. C. (2020). *Introduction to statistical quality control* (8th ed.). John Wiley & Sons.

Nashruddin, M. A. (2024). Analisis pengendalian kualitas produk karton box di PT Sinar Garuda Makmurindo dengan metode FMEA dan FTA. *JUSTI (Jurnal Sistem dan Teknik Industri), 5*(2), 135–140. https://doi.org/10.30587/justicb.v5i2.9373

Pande, P. S., Neuman, R. P., & Cavanagh, R. R. (2002). *The Six Sigma way team fieldbook: An implementation guide for project improvement teams*. McGraw-Hill.

Preziosi, M., Acampora, A., Lucchetti, M. C., & Merli, R. (2022). Delighting hotel guests with sustainability: Revamping importance-performance analysis in the light of the three-factor theory of customer satisfaction. *Sustainability*, *14*(6), 3575. https://doi.org/10.3390/su14063575

Riyanto, M., & Munir, M. (2024). Quality control of 240 ml cup product packaging using Six Sigma and FMEA methods to reduce product reject failure at PT. XYZ. *JKIE (Jurnal Knowledge Industrial Engineering).* https://jurnal.yudharta.ac.id/v2/index.php/jkie/article/download/6172/3125

Shah, A., Aliyev, R., Zeidler, H., & Krinke, S. (2023). A review of the recent developments and challenges in wire arc additive manufacturing (WAAM) process. *Journal of Manufacturing and Materials Processing*, *7*(3), 97. https://doi.org/10.3390/jmmp7030097

Stamatis, D. H. (2003). *Failure mode and effect analysis: FMEA from theory to execution* (2nd ed.). Quality Press.

Tahir, A. H., Adnan, M., & Saeed, Z. (2024). The impact of brand image on customer satisfaction and brand loyalty: A systematic literature review. *Heliyon*, *10*(16). https://doi.org/10.1016/j.heliyon.2024.e36254

Ulewicz, R., Czerwińska, K., & Pacana, A. (2023). A rank model of casting non-conformity detection methods in the context of industry 4.0. *Materials*, *16*(2), 723. https://doi.org/10.3390/ma16020723

Waruwu, A., Tampubolon, V. R., Pratama, M. A., & Putri, D. (2022). Pengendalian kualitas metode Six Sigma untuk mengurangi tingkat kerusakan produk kalender di PT. KLM. *IMTechno: Journal of Industrial Management and Technology, 3*(2), 82–90. https://doi.org/10.31294/imtechno.v3i2.1186

Yunian, B. T., Negoro, Y. P., & Priyana, E. D. (2024). Analisis pengendalian kualitas *packaging* tepung terigu kemasan 25 kg dengan metode Six Sigma dan *failure mode and effect analysis*. *G-Tech: Jurnal Teknologi Terapan, 8*(2), 1231–1241. https://doi.org/10.33379/gtech.v8i2.4231