Application of Six Sigma DMAIC Methodology for Defect Reduction in Conical Lighting Pole Manufacturing Process

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Abstract

This study uses the application of the Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) methodology to significantly reduce the defect rate of Conical Lighting Poles (CLPs). A high CLP defect rate directly impacted profitability and customer satisfaction, prompting the need for a structured improvement initiative. Utilizing the DMAIC framework, the problem and its impact were defined. The measure phase involved data collection to quantify the current defect levels. In the analyze phase, a cause-and-effect analysis was conducted to identify root causes, with Pareto charts highlighting the most significant contributors to defects. Furthermore, a brainstorming session with experts from manufacturing, quality control, and maintenance departments facilitated the development of targeted solutions in the improve phase. The control phase implemented measures to sustain the improvements. The results successfully demonstrate the efficacy of the DMAIC methodology, leading to a substantial improvement in Pp and Ppk, which increased from 3.23 to 6.22. In addition, the process achieved statistical control with no out-of-control points, indicating a more stable and capable manufacturing process. This research not only reduced defects but also enhanced overall operational efficiency and product quality.

Keywords:

Six Sigma, Quality, DMAIC Phases, and Manufacturing Process

Highlights:

- Validated modeling framework incorporates thermoelectric principles and geometric parameters.
- Critical design insights provided for µTEG applications in IoT and wearable technologies.
- Optimized temperature differences, leg area, and ceramic plate thickness improves heat transfer.

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1. Introduction

Six Sigma is a valued and efficient methodology widely utilized by enterprises and organizations to reduce expenses [1], minimize product defects [2], increase profitability [3], and improve customer satisfaction [4]. Six Sigma incorporates quality tools and statistical tools into a standardized methodology called DMAIC [5, 6], which is an acronym for define, measure, analyze, improve, and control. DMAIC enables the organization to identify the root cause of any issue. Six Sigma, initially developed by Motorola in the late 1980s, has indeed become a highly successful standard-quality initiative [7]. Motorola Corporation devised the Six Sigma methodology to attain exceptional quality, optimize profitability, and position itself as a frontrunner in its industry [8].

The manufacturing sector emphasized quality enhancement strategies, including total quality management (TQM) and continuous quality improvement (CQI). Nonetheless, the prevalence and impetus of TQM diminished owing to insufficient data-driven analysis, leading to widespread disillusionment among managers regarding the potential for quality enhancement [9]. Recently, Six Sigma was adopted to create and maintain competitive advantage while attaining long-term objectives. Six Sigma results in time and cost savings, revenue augmentation, metrics to assess current processes, outcomes or service quality, and the enhancement of crucial quality characteristics essential for both external and internal customers [10]. Six Sigma aims for superior quality outcomes, targeting less than 3.4 faults per million in all products, attributes, or production processes. Six Sigma originated on the shop floor and then transitioned into the front offices [11]. Recently, Six Sigma has gained popularity among various organizations and industries, including manufacturing, services, educational institutions, and banking.

There are untapped opportunities for exploring the full potential of applying Six Sigma in the service and manufacturing industries through various types of literature in different domains. To illustrate that, the integration and enhancement areas of Six Sigma with critical success factors for effective deployment of Six Sigma, different quality initiatives, and Six Sigma applications strategies. Therefore, in this paper, Six Sigma is used to analyze the problem of increasing CLP defects. This issue leads to reduce in profit and external customer dissatisfaction. The DMAIC approach was explained using a case study to handle the efficiency of the integration testing. This paper is organized as follows: Section 2 presents a comprehensive analysis of the existing literature on Six Sigma conducted by previous researchers. Section 3 delves into the concept of DMAIC. Section 4 provides an analysis of a specific case study and demonstrates the practical uses of DMAIC methodology. Section 5 presents the conclusion.

2. Literature Review

Six Sigma is a quality standard that aims for a success rate of 99.9997% with less than 3.4 errors per million opportunities [12]. This calculation considers a 1.5 Sigma shift in the process mean, which is used to determine the long-term variance. The term "Sigma" is used to indicate the level of variation in the process average. In the business realm, Six Sigma is a defined business strategy aimed at enhancing firm profitability by optimizing the efficacy and efficiency of all activities to meet or beyond customer wants and expectations [5]. In this section, Six Sigma types of research have been classified into four categories; tools and techniques of Six Sigma, Six Sigma in manufacturing organizations, and Six Sigma in service organizations.

2.1 Tools and Techniques of Six Sigma

Six Sigma characteristics are implemented via two primary methodologies: DMAIC (Define-Measure-Analyze-Improve-Control) and DMADV (Define-Measure-Analyze-Design-Verify) [5]. The DMAIC is utilized when an objective pertains to the enhancement of existing goods, processes, and services (PPSs) within a business. DMADV is utilized when the PPSs have not yet been established by the company and require creation and implementation. Antony [5] illustrated the application of design of experiments (DOE) alongside Six Sigma to ascertain the critical process parameters influencing the tensile strength of welded joints. Lazreg and Gien [13] devised quality function deployment, Six Sigma, and maintenance excellence methodologies to enhance the organizational maintenance function. The objective of this project was to reduce mistake rates and maintenance cycle durations. Yeung [1] illustrated the utilization of the SIPOC (Supplier, Input, Process, Output, and Customer) framework within Six Sigma to assess the efficacy of product and service providers, hence culminating in improved customer satisfaction. Process Capability, Gauge Repeatability and Reproducibility, One-Way and Two-Way Analysis of Variance, Cause-and-Effect Analysis, Pareto Chart, Failure Mode Effects Analysis (FMEA), and Design of Experiments have been employed to execute Six Sigma [11-14].

2.2 Six Sigma in Manufacturing Organizations

This section presents the implementation of Six Sigma in manufacturing Organizations. Furthermore, this paper includes case studies that demonstrate the practical application of Six Sigma in manufacturing firms of varying sizes, including small, medium, and large industries. The study of Antony et al. [13] Applied the Six Sigma DMAIC technique to address the issue of engine overheating in the automobile sector. Doble [14] assessed the chemical plant safety approach and the Six Sigma methodology in regard to chemical process safety. Safwat and Ezzat [15] presented the Six Sigma method for reducing the waste rate in a plastic injection molding business by utilizing the DMAIC technique. In the report, the average scrap ratio before and after the study period were compared. Deshmukh and Lakhe [16] implemented the Six Sigma DMAIC methodology to minimize waste in small and medium-sized companies that specialize in the production of corrugated boxes. The study cnducted by Su and et al. [17] demonstrates the application of the Six Sigma DMAIC methodology to analyze the manufacturing process of semiconductors. Specifically, they applied this method to the inter metal-dielectric process and showcased the effectiveness of the Six Sigma technique in reducing defects and waste. The study of Liu and Li [18] was carried out in Motorola management to showcase a typical example of the use of the Six Sigma technique's DMAIC phases in the context of supply chain human resources. This study specifically focused on the improvement of third-party contractor hiring and training processes.

The study successfully accomplished its objective of minimizing the duration of the hiring process, while also demonstrating the cost-effectiveness and ease of implementation of DMAIC. Jirasukprasert and et al. [19] utilized the principles of Six Sigma and the DMAIC technique to analyze flaws, identify root causes, and develop a solution to eliminate the issue of leaky gloves. The study of Gupta and Garg [20] Utilizes the Six Sigma DAMIC technique to identify and examine the primary factors contributing to the damage issue in Aluminum Composite Panel sheets at Y firm. This problem results in financial losses, reduced market presence, diminished earnings, and customer discontent.

3. DMAIC Methodology

Six Sigma methodology for improving processes by reducing errors and process variation is the DMAIC phases, which stand for Define, Measure, Analyze, Improve, and Control. Figure 1 depicts the DMAIC phases, with each step being expounded upon as follows: The DMAIC technique delineates a definitive strategy for the implementation of Six Sigma initiatives [10]. The initial phase (define) commences with the identification of opportunities, the clarification of objectives, and the establishment of goals.

Opportunities for improvement are identified through the voice of the customer (VOC). During the measuring phase, the gathered data is analyzed to assess the initial performance in relation to customer requirements. The third phase (analyze) involves the examination of the root cause(s) responsible for the mistakes or faults, which are quantified through data collection. In the fourth phase (improve), potential solutions to eliminate the underlying cause(s) or mistakes or flaws are evaluated, and the ideal solution(s) is selected. The system's performance is assessed following the implementation of process enhancements. The final step (control) involves the creation and execution of a monitoring system aimed at reducing future errors, together with the reporting of outcomes and recommendations.

4. Case Study

4.1 Define phase

At one of the manufacturing companies which engaged in the manufacture and marketing of columns and masts, lighting and distribution panels, power and communication towers, steel structures, steel pipes, And irrigation systems. In this topic, it’s noticed from the reports coming from this Company there are huge defects of Conical Lighting Poles (CLPs). The paper describes the fundamentals and methods of Six Sigma,

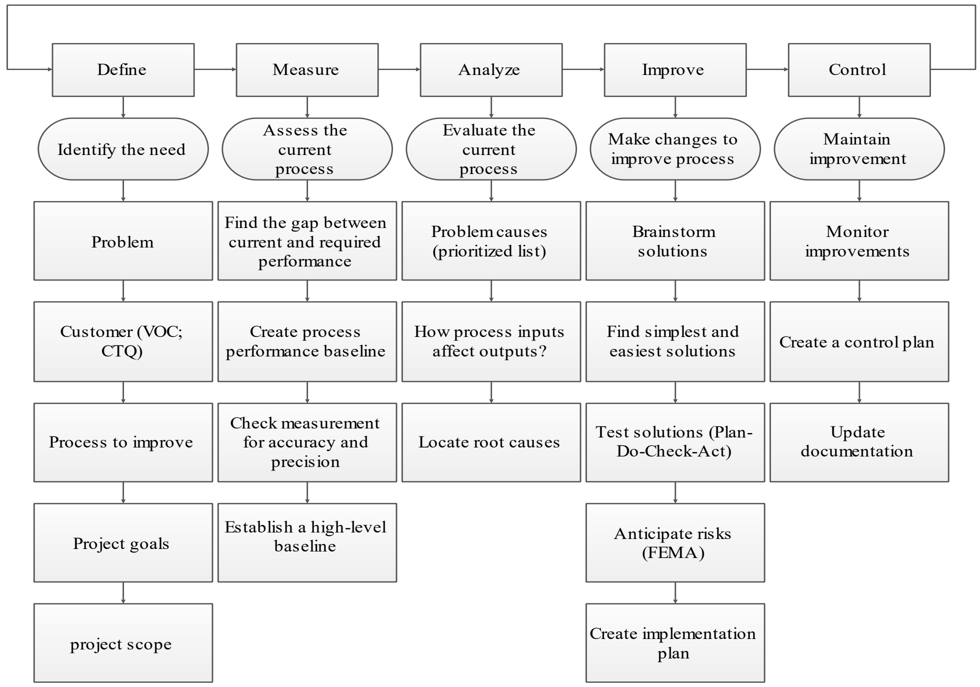

Figure 1. The DMAIC methodology.

one of the best approaches for quality control and enhancement. Specifically, the Six Sigma problem-solving and improvement paradigm known as DMAIC (Define-Measure-Analyses-Improve-Control) is employed. Numerous statistical and quality-improving instruments, such the fishbone diagram, Pareto chart, and SIPOC Analysis, have been employed under the purview of this paradigm. The objectives are to identify what's important to the customer (VOC) and to initiate data collection and financial or business benefits.

4.1.1. Problem Statement

Nowadays, the competition in industrial organizations has become tough, especially in the fast-moving commodity production (FMCG) and to ensure the loyalty of the customer to the acquisition of these goods and gain new customers. So, the company should provide a product that meets customer stratification at the highest possible quality level and lowest prices. In this study, we will seek the possible reasons for the CLP defects.

4.1.2. Goal Statement

Eliminate the main reasons for recurring the CLP defects as possible.

4.1.3. A SIPOC Analysis

The SIPOC (Suppliers, Inputs, Process, Outputs, and Customers) analysis was conducted to create a thorough understanding of all essential internal customers, their needs, and the supplier dependencies and associated process steps for the Conical Lighting Pole (CLP) product. The SIPOC diagram (Figure 2) visually represents this, showing:

- Suppliers: Planning and material management department, cutting process, forming process, welding process, galvanizing process.
- Inputs: Metal sheets finished metal sheets, conical metal sheets, conical lighting poles, and final products.
- Process: Cutting process, forming process, welding process, galvanizing process, summarizing and report costs.
- Outputs: Finished metal sheets, conical metal sheets, conical lighting poles, final products, and analyses of defect reports.
- Customers: Production Department, Quality Department.

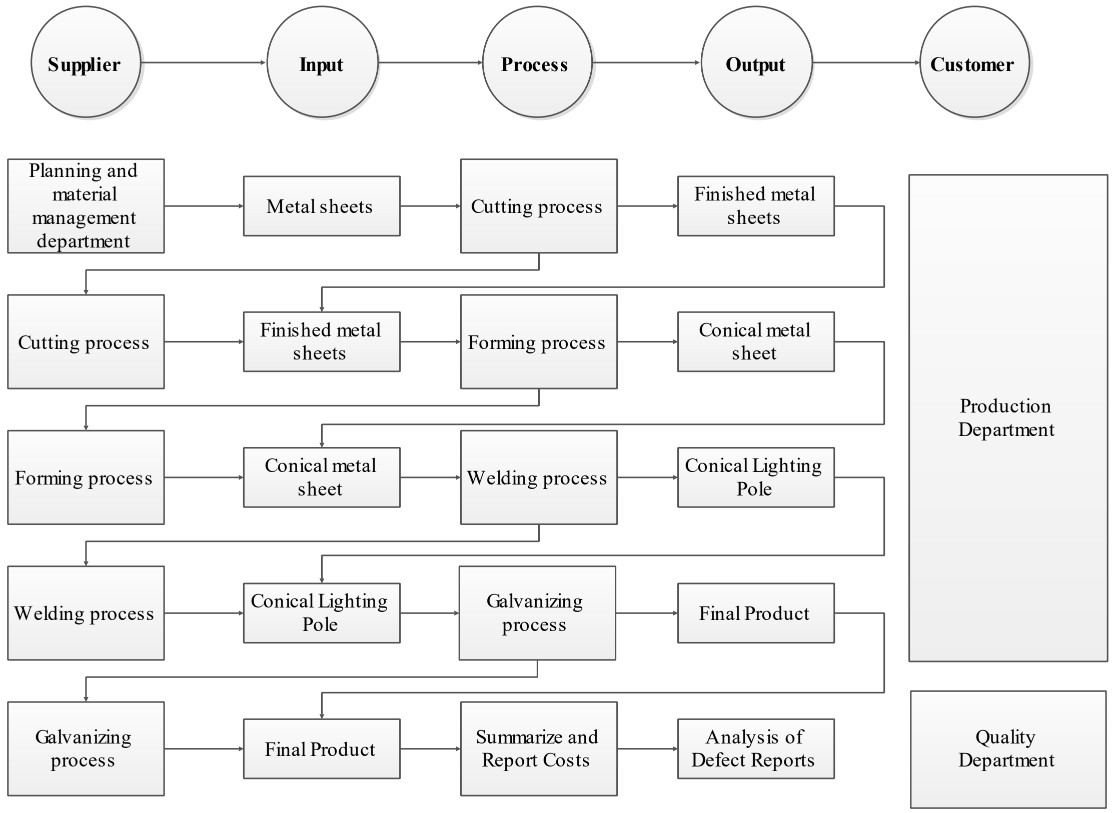

Figure 2. SIPOC Analysis for CLP Product.

The SIPOC analysis helped to gain a comprehensive understanding of the situation and pinpoint areas requiring enhancement. While the diagram lays out the steps, there are no specific gaps identified in supplier inputs during the SIPOC analysis itself. However, the subsequent analysis phase did identify defective incoming material (raw material) as a cause of defects, suggesting a potential gap or issue with supplier quality control that was later addressed through periodic inspection of storage.

4.1.4. Flow chart of the product

The provided flowchart (Figure 3) details the manufacturing process for a Conical Lighting Pole (CLP), commencing with raw materials that undergo a cutting process, followed by a quality check that either advances acceptable material or diverts unacceptable material for alternate use. Subsequently, the material proceeds to a forming process, which, if successful, leads to welding; otherwise, defects are handled, with successful resolution leading back to welding, or irrecoverable defects resulting in rejection/scrap. After welding, the CLP is galvanized, and a final quality check determines if it is sent to storage or if galvanizing defects need handling, with successful handling leading to storage and irreparable issues resulting in rejection/scrap, ultimately illustrating the sequential steps, quality control points, and defect management strategies within CLP production.

4.2. Measurements phase

4.2.1. Define of the Conical Lighting Pole defects

The defects of the CLP product can be defined as up-and-down scratches due to the forming machine, as shown in Figure 4. In this study, a Conical Lighting Pole (CLP) with a standard height of 6 meters and a thickness of 5 mm was considered for analysis. A sampling procedure is used for process quality monitoring based on a moving average control chart.

4.2.2. Data Collection

From October 1 to December 31, 2018, thickness data for the CLP (conical lighting pole) were collected through a sampling procedure. A significant portion of this data was found to be out of control. Table 1 displays 30 samples of the collected thickness data, each representing a CLP tested during this period. In

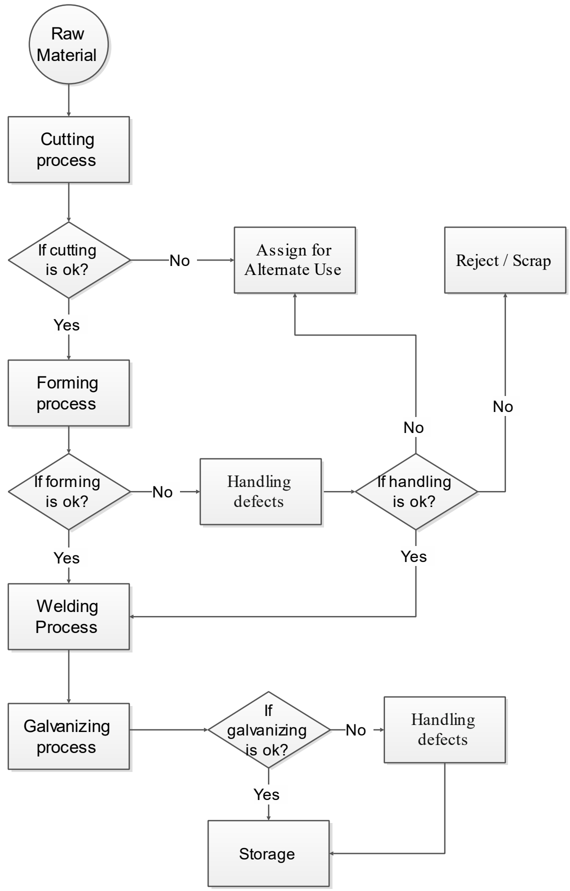

Figure 3. Flow chart of the CLP product.

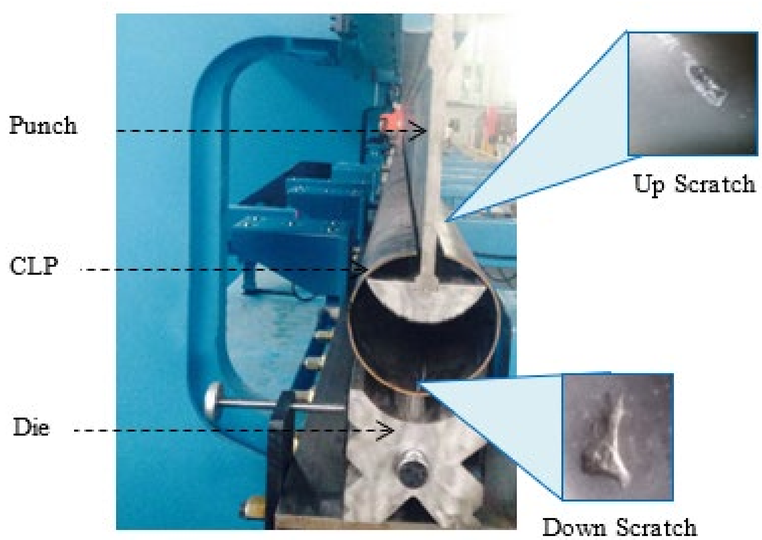

Figure 4 . Up and down scratched of CLP.

addition, Table 2 presents the analysis of the total defects taken in the same period.

Table 1. Number of defects and thickness data of the CLP.

Sample	Thickness (mm)	Sample	Thickness (mm)
1	4.2	16	5.2
2	4.3	17	5.2
3	4.5	18	5
4	4.5	19	4.8
5	4.5	20	4.5
6	4.6	21	4.2
7	4.5	22	4.2
8	4.5	23	4.5
9	4.6	24	4.8
10	4.8	25	5
11	5	26	4.7
12	5.2	27	5
13	5.8	28	5
14	5.7	29	4.8
15	5.5	30	5

Table 2. Total defect rates of CLP from October 1 to December 31, 2018.

Category	No. of Cases	% Defect rates
Use as is	58	14.95%
Repair/ rework	325	83.76%
Assign for alternate use	2	0.52%
Reject/ scrap	3	0.77%
TOTAL	388	100.00%

4.2.3. Control chart

Figure 5 presents a Moving Average (MA) chart illustrating the thickness (mm) of CLP defects, a statistical process control tool designed to monitor process stability over time. The chart displays the moving average of thickness measurements across 30 samples. The central green line denotes the overall mean ($\bar{\bar{X}}$) of the moving averages at 4.803 mm. The red lines indicate the Upper Control Limit (UCL) at 5.141 mm and the Lower Control Limit (LCL) at 4.466 mm, establishing the expected range of variation for a stable process. The plot points, marked by blue circles and red squares, represent the calculated moving average for each sample. Deviations from these limits or non-random patterns (e.g., trends or shifts) signal a potentially out-of-control process, necessitating investigation to pinpoint and resolve the root causes. In this particular chart, samples 13-17 exceed the UCL, and samples 1-3 and 21-22 fall below the LCL, suggesting the process was out of control at these points. The control limits for this MA chart were determined using the overall process mean ($\bar{\bar{X}}$) and an estimated process standard deviation (σ), adjusted by the square root of the moving average span (w). Specifically, the UCL is calculated as $\bar{\bar{X}} + 3\frac{\sigma}{\sqrt{w}}$ and the LCL as $\bar{\bar{X}} - 3\frac{\sigma}{\sqrt{w}}$. Assuming a moving average span (w) of 2, the estimated standard deviation (σ) of individual measurements would be divided by $\sqrt{2}$ before being multiplied by 3 and then added to or subtracted from the overall mean of 4.803 mm to derive the UCL and LCL values displayed.

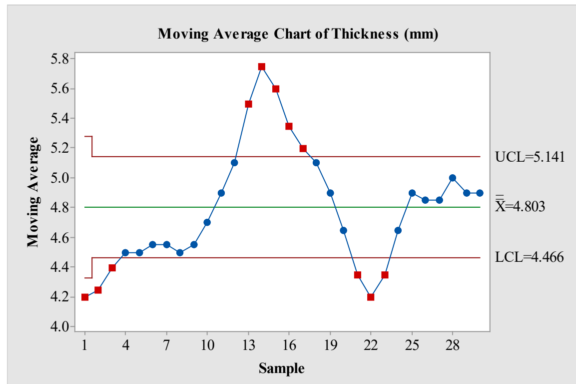

Figure 5. Moving average chart for CLP defects.

4.2.4. Process capability

Figure 6 shows the process capability analysis for thickness (mm) and provides a detailed statistical summary and a capability histogram. The histogram visually represents the distribution of the thickness data, showing it against the Lower Specification Limit (LSL), Target, and Upper Specification Limit (USL). The overall distribution (dashed line) appears wider than the within-group distribution (solid line), suggesting potential sources of variation over time. Key capability indices are provided, with Pp and Ppk (Overall Capability) being 3.23 and 3.23, respectively, and Cp and Cpk (Potential (Within) Capability) being 8.49 and 8.4,9, respectively. The significant difference between the "Overall" and "Within" capability indices, particularly for Ppk vs. Cpk, indicates that there is substantial variation over time, even if the short-term process is highly capable. The report also includes "PPM" (Parts Per Million) values, showing a high number of expected defects both below the LSL and above the USL, leading to a total of 419,549.25 PPM for the overall process.

Figure 7 shoes the process capability Sixpack analysis for thickness (mm) and offers a more dynamic

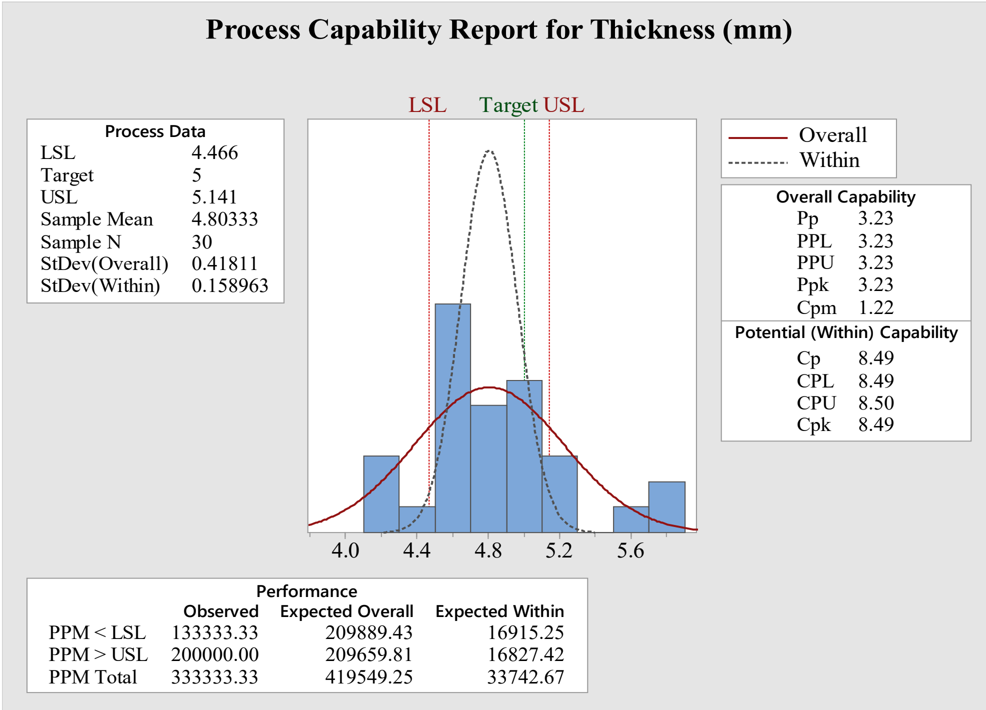

Figure 6. Process capability analysis for CLP defects.

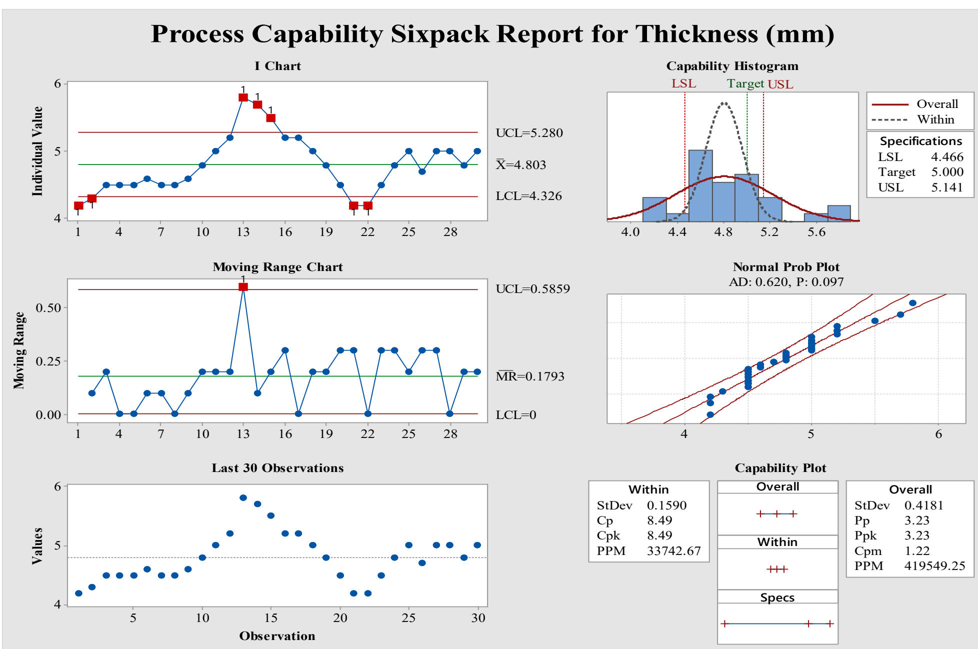

Figure 7. Process Capability Six-pack Report of CLP defects.

view of the process behavior over time. The "I Chart" (Individual Chart) shows the individual thickness measurements over 30 observations, with an out-of-control point at observation 13 (marked with '1'), indicating a special cause of variation. The "Moving Range Chart" also shows an out-of-control point around observation 13, reinforcing the presence of a special cause. The "Last 30 Observations" plot reiterates the raw data trend, clearly showing the outlier at observation 13. The "Normal Prob Plot" (Normal Probability Plot) assesses the normality of the data distribution, and with an Anderson-Darling (AD) value of 0.620 and a p-value of 0.097, the data generally appear to follow a normal distribution, though the outlier might influence this. The "Capability Histogram" is a smaller version of the one in the first report, and the "Capability Plot" graphically displays the Pp, Ppk, Cp, and Cpk values, again highlighting the discrepancy between the overall and within-process capabilities. The out-of-control points on the control charts, particularly the I Chart and Moving Range Chart, suggest that the process is not stable and predictable, and the root cause for these points should be investigated before solely relying on the capability indices.

4.3. Analysis Phase

Analysis of CLP defects as shown in Table 3. The analysis shows four categories of defect types; the most common category is manufacturing error, with 82.21 percent. Table 3 shows the types of causes of the defects that the product received in varying proportions, depending on the type of defect. For example, wrinkles or deep scratches occur due to process errors caused by the failure of the Punch or the Die, minor scratches occur due to equipment errors caused by the collision of the product with other things, and so on.

Two Pareto charts were used to highlight specific factors:

- Main Causes Pareto Chart (Figure 8): This chart highlighted "manufacturing error" as the most significant main cause, accounting for 82.36% of defects, followed by "handling defects in galvanizing" (6.96%), "handling defects in fabrication" (6.19%), and "incoming material defective" (4.64%).

- Root Causes Pareto Chart (Figure 9): This chart delved deeper into the root causes, identifying "equipment error" (45.36%) and "operator error" (20.36%) as the most dominant root causes, collectively accounting for over 65% of total losses. Other root causes included "process error," "damage or bend in finishing CLPs," and "dent due to handling in finishing CLPs".

These highlighted factors significantly influenced the improvement strategy by directing the improvement team to concentrate on lowering these specific errors. The proposed solutions directly address these identified main and root causes, focusing on preventive maintenance for equipment, training for operators, and improved handling and storage practices.

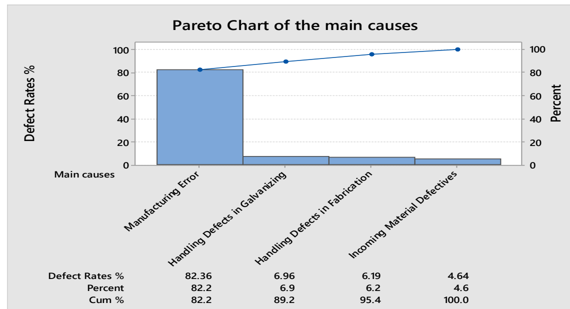

Figure 8. Pareto Chart of the main causes of CLP defects.

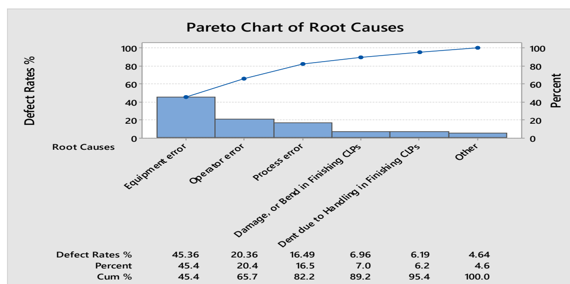

Figure 9. Pareto Chart of the root causes of CLP defects.

The analysis was conducted to recognize the root cause(s) of the problem. A brainstorming session was held to discover potential reasons for the faults, drawing on the experience of the management and improvement team members. The cause-and-effect diagram aims to categorize and illustrate the possible root causes of the problem. Upon completion, the diagram aids in identifying the main problems and offers suggestions for enhancement. Typically, a cause-and-effect diagram encompasses four primary categories: personnel, equipment and tools, raw materials, and maintenance. The basic reasons are illustrated in the cause-and-effect diagram depicted in Figure 10.
The schematic analysis reveals the primary sources of the CLP problems as follows:

Table 3. Analysis of causes of CLP defects.

Category		No. of Cases	Defect Rates %
Manufacturing error	Operator error	79	20.36%
	Equipment error	176	45.36%
	Process error	64	16.49%
Incoming Material defective	Raw material	18	4.64%
Handling defects in the fabrication area	Dent due to Handling in Finishing CLPs	24	6.19%
Handling defects in Galvanizing	Damage, or Bend in Finishing CLPs	27	6.96%
TOTAL		388	100%

The schematic analysis reveals the primary sources of the CLP problems as follows:

- Lack of training, experience, and responsibility.
- Equipment & tools, Punch & Die components of the forming machine.
- Raw material defective due to corrosion or humidity.
- None enough preventive maintenance.

4.4. Improve Phase

To reduce the CLP defects due to the obtained causes, several solutions are suggested. These solutions are considered for each root cause. A brainstorming session was carried out with experts from the manufacturing, quality control, and maintenance departments, resulting in the formulation of solutions. Furthermore, the solutions were "constructed with improvement team members. Developed policy has proposed a preventive maintenance interval (TPM) and showed the time a job is to be performed for preventive maintenance for the Punch and the Die components that form a CLP, to check for possible failure. This preventive maintenance interval should be taken one time every 144 hours (every two working weeks), and with only SR 43.3 expected total cost per hour, compared to the cost of lost production incurred by the company every hour and estimated at SR 52.15 due to product defects, not to mention the waste of time lost due to the repairing of these defects. Table 4 shows the developed solution for the root causes, which should be applied to minimize defects.

After making the applications of maintenance actions on the forming sheet metal machine and training workers, and qualifying them well for the entire year. The company was able to eliminate the causes of major and root defects. Table 5 displays the thickness measurements of the CLP following the implementation of the improvement measures.

4.5. Control Phase

The objective of the "control" phase is to effectively sustain the improvements achieved by the offered remedies, hence preventing the reoccurrence of problems.

4.5.1. Control charts

Figure 11 shows the moving average chart for CLP defects after improvement. Comparing the original "Moving Average Chart of Thickness (mm)" with the "Moving Average Chart of Improved Thickness (mm)," the primary improvement is the achievement of statistical control in the latter chart, as all data points now consistently fall within the calculated control limits, signifying the removal of assignable causes of variation and resulting in a more stable and predictable process. While the process mean has shifted upwards from 4.803 mm to 5.0333 mm and the control limits have slightly widened (from a range of 0.551 mm to 0.5966 mm), this change in mean could be a targeted improvement depending on the desired thickness for "CLP defects," and the overall stability gain outweighs the slight increase in limit range by eliminating out-of-control points that were prevalent in the original chart (e.g., samples 13-17 above UCL, and 1-3, 21-22 below LCL).

4.5.2. Process capability after improved

Figure 12 presents the process capability analysis and shows a significant enhancement in the distribution of thickness data.

Table 4. The proposed solution for obtained root causes from the improve phase.

Defect Cause	Root Cause	Proposed Solution
Lack of preventive maintenance	Wrinkles on the sheet metal component features. Scratches along with the component of forming machines. Small pieces of iron scrap on the Die that cause sheet metal stamping.	1. Adjustment of the punch component correctly. 2. Eliminate the deep scratches on the Die by welding. 3. Eliminate and clean the pieces of the remains of iron scraps on the Die equipment periodically.
Lack of regular inspection equipment	Leading to downtimes of components of machines	1. Create a checklist to delineate inspection tasks, regulate inspection operations, and furnish a report of inspection activities for equipment. 2. Perform continuous, pre-operational, and periodic inspections on the essential components of the equipment.
Operator errors	Incorrect operation	Periodically training of each operator.
Equipment errors	Collision the sheet metal or the product with other objects.	Periodically control of equipment.
Handling defects in galvanizing	Dent, deformation, damage, or bend of CLPs.	Provide an appropriate galvanizing area for handling defects.
Handling defects in the fabrication area	Dent due to handling in finishing CLPs.	Provide an appropriate fabrication area for handling defects.
Incoming material defective	Defect or damage the raw material through storage.	Periodic inspection of storages.

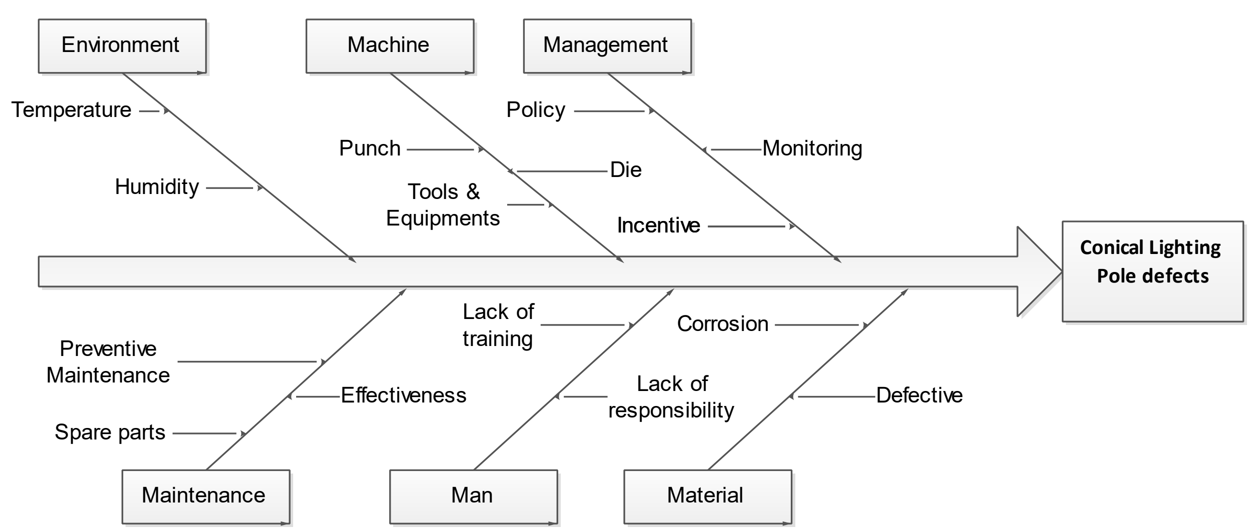

Figure 10. Cause-and-effect diagram related to CLP defects.

Table 5. Thickness data of the CLP after the.improvment.

Sample	Thickness (mm)	Sample	Thickness (mm)
1	4.7	16	5.2
2	4.8	17	5.2
3	4.8	18	5
4	5	19	4.8
5	5.2	20	4.7
6	5.3	21	4.7
7	5.2	22	5
8	5	23	5.2
9	5	24	5.2
10	4.8	25	5
11	5	26	5
12	5.2	27	5.2
13	5.2	28	5
14	5	29	4.8
15	5.3	30	5

The histogram now appears more centered around the target of 5 mm, and the spread is considerably reduced compared to the previous state. The specification limits (LSL 4.735, USL 5.3316) are clearly defined, and the majority of the data falls within these bounds. The "Overall Capability" indices, Pp and Ppk, have significantly improved to 6.22, indicating a much more capable process in the long run. Similarly, the "Potential (Within) Capability" indices, Cp and Cpk, are also high at 8.49 and 8.48, respectively. The "PPM Total" has drastically decreased to 11,985.42 (Overall) and 33,896.39 (Within), signifying a substantial reduction in defects. While there's still a slight discrepancy between Overall and Within PPM, the improvement is remarkable, indicating successful efforts in reducing overall process variation.

Figure 13 provides a more granular view of the process stability and distribution after the improvements. The "I Chart" (Individual Chart) for "Improved Thickness" shows a process that appears to be in statistical control, with all individual data points falling within the control limits (UCL 5.455, LCL 4.611) and no clear patterns or trends, unlike the previous report, which had an out-of-control point. The "Moving Range Chart" also indicates a stable process, with all moving ranges within the control limits, although there is one point close to the UCL. This stability is a crucial indicator that the process is predictable. The "Last 30 Observations" plot reinforces the visual stability of the process. The "Normal Prob Plot" now shows an AD value of 1.352 with a p-value of less than 0.005, which might suggest a slight deviation from strict normality, although the process visually seems well-behaved within the specifications. The "Capability Histogram" confirms the tighter distribution, and the "Capability Plot" reiterates the high Pp, Ppk, Cp, and Cpk values, further demonstrating the significant improvement in process capability and stability.

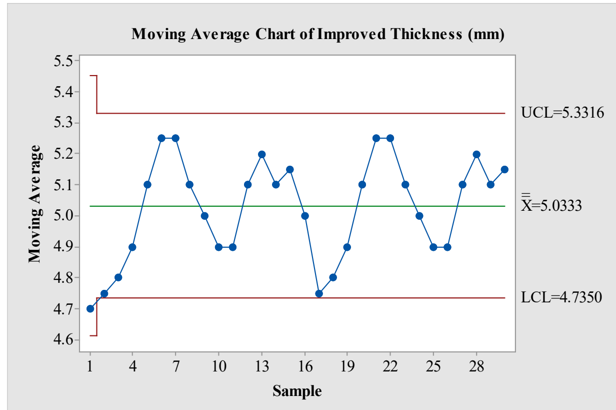

Figure 11. Moving average chart of CLP defects after improvement.

5. Conclusion

This study presents the utility of the DMAIC Six Sigma methodology to reduce the CLP defects in the forming production machine at one of the manufacturing companies. Initially, the SIPOC methodology was employed to gain a comprehensive understanding of the situation at hand and to pinpoint the specific areas that require enhancement. Subsequently, the data were collected over three months and subjected to analysis utilizing Minitab software. Subsequently, the Pareto chart was utilized to direct attention towards the primary and significant underlying reasons. Furthermore, a brainstorming session was carried out with experts from the manufacturing, quality control, and maintenance departments, as well as management and improvement team members. This session resulted in the formulation of solutions. The ideas generated were based on the identified root causes from the cause-and-effect diagram and Pareto charts. The proposed solutions reflect the ideas generated, which focused on addressing the lack of preventive maintenance, the lack of regular inspection, operator errors, equipment errors, handling defects in galvanizing and fabrication areas, and incoming material defects. The prioritization of these ideas was implicitly based on the Pareto analysis, which highlighted manufacturing errors (equipment and operator errors) and handling

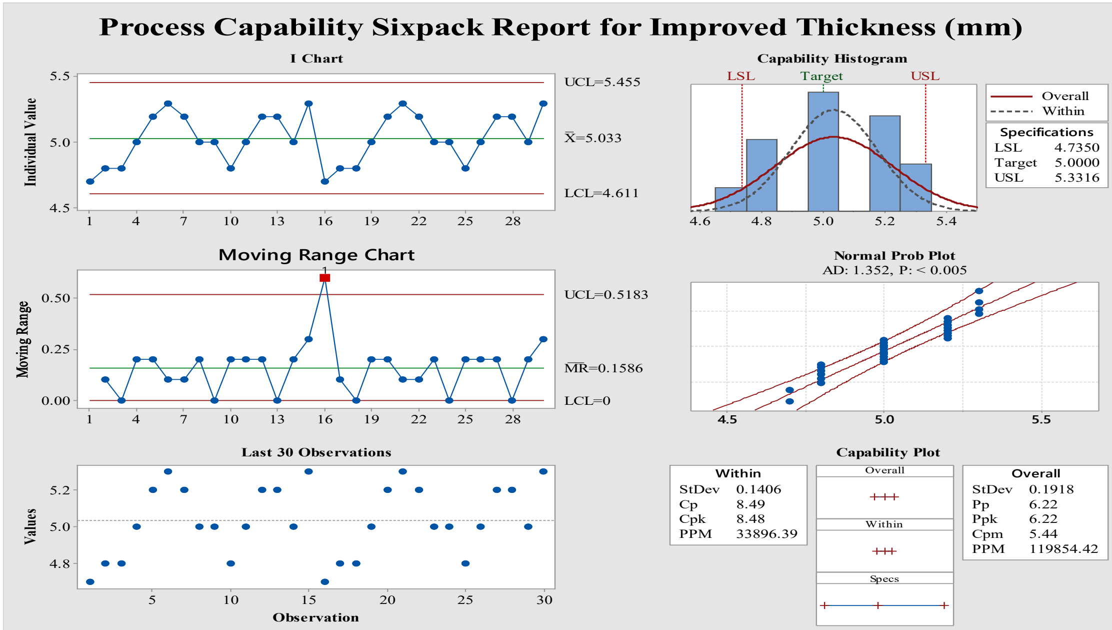

Figure 12. Capability Six-Pack for CLP defects after controlling.

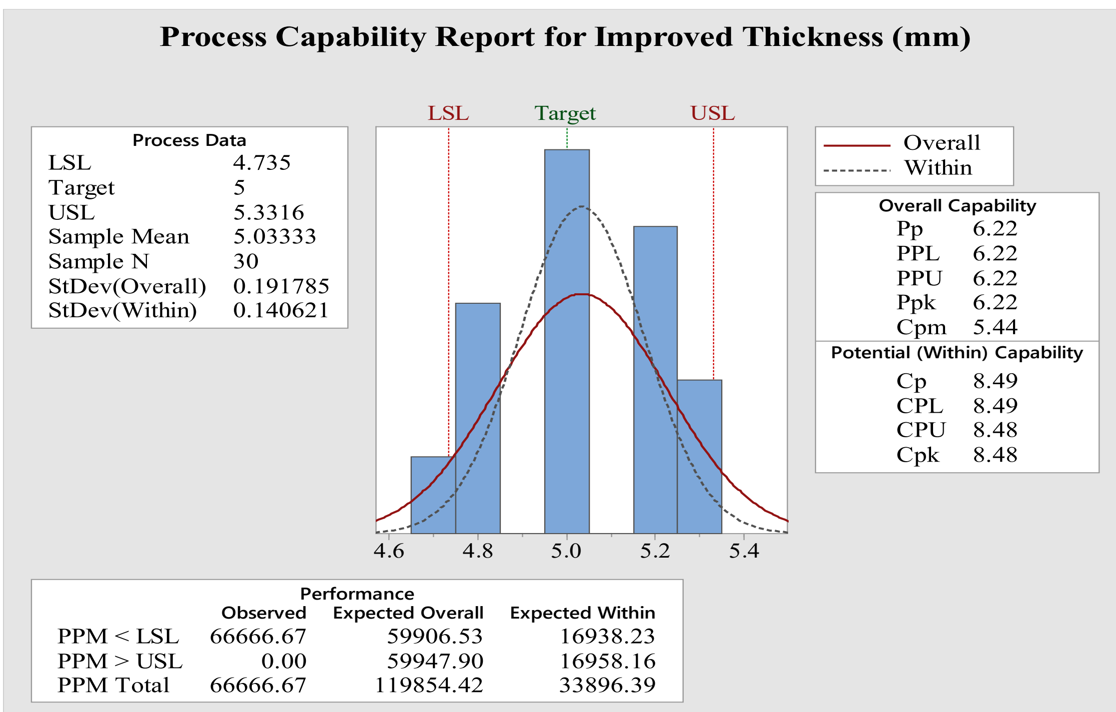

Figure 13. Process capability analysis for CLP defects after controlling.

defects as the most significant contributors to the overall defects, thus guiding the improvement team to concentrate on lowering these errors first. The conclusion emphasizes the importance of consistently maintaining the improvements achieved to meet the necessary criteria. Future research could explore the long-term sustainability of the improvements, the application of Six Sigma in other areas of the company, a more detailed cost-benefit analysis of all solutions, or a comparative study with other quality improvement methodologies in similar manufacturing contexts.

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