Quality System Improvement Using Sustainable Lean Manufacturing and Six Sigma in the Heavy Components Industry

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Research Article

Quality System Improvement Using Sustainable Lean Manufacturing and Six Sigma in the Heavy Components Industry

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Abstract: This study applied quality system improvement using sustainable lean manufacturing and the six-sigma approach in the heavy component industry using the plan–do–check–action (PDCA) cycle. This study aimed to constitute the application quality system improvement as the integration of statistical process control, lean manufacturing, Six Sigma, sustainable awareness, and Quality 4.0 in the heavy component manufacturing industry. Improvement strategies were implemented using tools such as Sustainable Value Stream Mapping (SVSM), manufacturing, Process Activity Mapping (PAM), and decision tree CART classification analysis. Key improvements included the implementation of jig redesign, use of QR code scanners, making a finishing table in the production process, regular cleaning of welding tools, and visualization of data with the Power Business Intelligence dashboard. Post-intervention analysis demonstrated an improved sigma level of 3.748 from 3.361. PCE increased from 82.71% to 83.72%. The results of the indicator values. The average sustainability category is in the yellow traffic light condition, namely 61%–90%, which means that this indicator can still be improved to achieve the company's targets. After implementing this concept, the company can produce more efficient processes. The proposed quality system improvement model significantly enhances process quality and operational sustainability in the heavy component industry.

Keywords: Lean manufacturing; Quality 4.0; Quality system; Six Sigma; Sustainable

1. Introduction

The research was conducted in the heavy component industry, focusing specifically on the production processes of PC200 Buckets and Brackets. These components have exhibited several operational challenges, particularly in meeting customer demand with consistent quality. Two case studies were conducted on analyze the issues within these processes. Delays in order fulfillment have been attributed to excessive work-in-progress inventory and inefficiencies on the production floor. Moreover, the production system suffers from eight manufacturing wastes: overproduction, excess inventory, defects, unnecessary transportation, excessive motion, waiting, overprocessing, and underutilized talent. The problem of competition in the world of the heavy component industry is that it is getting tougher, and demand continues to increase. Based on these problems, the industry must be able to conduct more efficient production and improve product quality. Based on observations on the production of PC200 Buckets and Brackets, there is waste such as defects, overprocessing, motion, and waiting. These inefficiencies affect deliv-

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ery performance and product quality and diminish the company's sustainability performance across economic, environmental, and social dimensions. Application of sustainable value stream mapping as a tool to improve sustainability performance.

The research objective was to develop a quality system improvement model by integrating approaches of Statistical Process Control, Sustainability Awareness, Lean manufacturing, Six Sigma, and Quality 4.0 using Decision Tree CART classification and Power Business Intelligence through the Plan–Do–Check–Action (PDCA) cycle. The goal is to reduce waste, enhance production quality, and elevate the company's sustainability awareness.

There are many studies about quality that have been conducted. The modification of water dispenser items in response to customer needs and preferences, achieved by combining the Value Engineering and Quality Function Deployment approaches, resulted in improvements (Ginting, Silalahi, and Marunduri, 2025). The redesigned product incorporates buffer foam to improve patient comfort, aluminum in place of iron to lighten the product's weight, and uses quality function deployment (Ginting, Napitupulu, et al., 2025). Polyvinyl alcohol was used to enhance the quality of cassava starch-based wood bioadhesive (Budhijanto et al., 2024). The quality of beef was monitored in real-time through temperature, humidity, and the position of the distribution vehicle by designing a radio frequency identification (RFID) traceability system to ensure the distribution of halal (Sucipto et al., 2025). Quality 4.0 is the integration of Industry 4.0 technology with quality management, promising transformative potential through sustainable practices, predictive analytics, and real-time monitoring (Lubaba et al., 2025).

Numerous studies have examined the application of Six Sigma to enhance production quality across industries. For example, research has demonstrated the effectiveness of Six Sigma in reducing bottle production defects (Fitriana, Saragih, and Larasati, 2020). Data mining techniques are further integrated with Six Sigma for quality improvement in common rail component manufacturing (Fitriana, Saragih, and Fauziyah, 2020). It found implications and provided a roadmap for enhancing the quality of cosmetic packaging with the Six Sigma and data mining approach (Ramadhani et al., 2023). It emphasized critical success factors in sustaining Six Sigma initiatives, such as employee competence and leadership engagement (Bagherian et al., 2024), while it showcased its use in pharmaceutical manufacturing (Reddy et al., 2024).

Much research has been conducted on the Plan Do Check Action (PDCA) cycle. PDCA was applied in healthcare settings to lower the incidence of postoperative infections in patients with open fractures and antibiotic resistance (Bao et al., 2024). In PDCA cycle management, a method was used to teach anesthesiology trainees in a teaching tertiary care hospital how to perform RA puncture and cannulation (Zhang et al., 2024). The effectiveness of applying the PDCA strategy to raise the standard of nursing care has been investigated (Tamher et al., 2021). Indonesia prioritized patient-centered care, excellent nurse administration, and affordable medical costs regarding nursing care quality. The Indonesian government used Plan–Do–Study–Act PDSA tools in their quality improvement initiative, which was integrated into the electronic health record using the first three "Six Core Elements" of the HCT framework (Arons et al., 2024).

The Lean Six Sigma framework has been widely adopted in various industries to streamline processes and reduce waste. Applications that demonstrate operational and environmental benefits include healthcare (Montella et al., 2016), automotive (Guleria et al., 2021; Ruben et al., 2017a), and manufacturing processes (Amrina and Zagloel, 2019).

Sustainability research focuses on the effective implementation of developmental programs to support the concept of smart sustainable cities (Mahdzir et al., 2024). The study expanded cleaner and sustainability by cascading down key business objectives by creating a balanced, integrated, and hierarchical Sustainable Cleaner Maintenance Performance Measurement Framework (Sari et al., 2021).

A growing body of literature explores the intersection of lean and sustainability. Studies have emphasized sustainable maintenance and production practices as essential components of long-term industrial performance (Dey et al., 2019; Khodeir and Othman, 2016; Marie et al., 2020).

Green Lean Six Sigma (GLSS) is an integrated approach that optimizes operational efficiency while promoting environmental and social sustainability (Rathi et al., 2022; Fatemi and Franchetti, 2016; Gholami et al., 2021; Ruben et al., 2017b; Erdil et al., 2018). The research had advanced integrated frameworks that combine sustainability with Lean Six Sigma and Industry 5.0 technologies (Rahardjo et al., 2023). Key barriers in the construction sector have been identified, such as a lack of employee awareness, political instability, government policy, fund insufficiency, and top management commitment (Hussain et al., 2019).

Several studies have been conducted on smart manufacturing, sustainable lean Six Sigma in Industry 4.0, and the circular economy. This study offers a novel integrative framework to investigate the interactions between Industry 4.0 technologies and lean manufacturing, agile manufacturing, and circular manufacturing to improve sustainability performance in manufacturing companies (Elnadi et al., 2025). This study reviewed the literature on a possible model for integrating the four management paradigms: lean, green, circular economy, and Industry 4.0, while considering DFX techniques (Benabdellah et al., 2024).

The literature review reveals that the research gap is that no paper has discussed the integration of statistical process control, lean manufacturing, six sigma, sustainable awareness, industry 4.0, and power business intelligence in the heavy component industry.

The novelty of the research lies in the integration of statistical process control, lean manufacturing, Six Sigma, sustainable awareness, and Quality 4.0, utilizing decision trees and power business intelligence in the heavy component manufacturing industry. This study contributes to the field by proposing an integrated model that leverages all methodologies to address operational inefficiencies and enhance sustainability performance.

2. Methods

This study employed an integrated approach that combines statistical process control, lean manufacturing, six sigma, sustainable awareness, and quality 4.0. It used decision trees, CART classification, and power business intelligence, structured through the plan–do–check–action (PDCA) cycle. The objective was to improve the production quality and operational efficiency of the heavy equipment component industry, specifically for PC200 Bucket and Bracket production, while aligning improvements with the three pillars of sustainability: economic, social, and environmental. The "Plan" stage began with problem identification and root cause analysis using the Quality Control Sheet as the foundation tool. A SIPOC diagram (supplier, input, process, output, and customer) was constructed to map the entire process flow and clearly understand where inefficiencies existed. Critical to Quality (CTQ) elements were identified, followed by measurements on process capability, the Defect Per Million Opportunities (DPMO) value, and the sigma value. The Sustainability Awareness Model was introduced to align production goals with sustainability objectives. This model enabled the assessment of how production activities impacted the economic, social, and environmental dimensions of the organization. A SVSM was developed using these inputs to visualize waste and process inefficiencies across the value chain. This step involves categorizing the process steps into three categories: value-added (VA), necessary non-value-added (NNVA), and non-value-added (NVA) activities. In addition, PAM was conducted in conjunction with 3R analysis (reduce, reuse, and recycle) to identify and minimize resource usage, optimize the reuse of materials and components in the production process, and recycle materials to minimize negative environmental impacts.

Every control chart has a central line (CL), which is the middle boundary of the control chart. The upper control limit (UCL) is the upper limit of the control chart, while the lower control limit (LCL) is the lower limit of the control chart. Formula of the P attribute control chart (Fitriana et al., 2021; Montgomery, 2013).

This chart would actually function by taking successive samples of n units. The fraction nonconforming control chart's center line (CL, upper control limits (UCL), lower control limit (LCL) would therefore be as follows based on equations (1), (2), (3).

$$CL = \bar{p} = \frac{total\ defective\ units}{total\ inspection\ units} \tag{1}$$

$$UCL = \bar{p} + 3\sqrt{\frac{\bar{p}(1-\bar{p})}{ni}} \tag{2}$$

$$LCL = \bar{p} - 3\sqrt{\frac{\bar{p}(1-\bar{p})}{ni}} \tag{3}$$

The Calculation of DPMO and sigma levels are used to measure process performance (Fitriana et al., 2021).

The unit's complexity is not immediately taken into consideration by the DPU measure. Defect per unit is based on equation (4), Defect per opportunities is based on equation (5) The defect per million opportunities (DPMO) measure is based on equation (6). Sigma Level is based on equation (7)

1. Defect per unit (DPU)

$$DPU = \frac{Defect}{Unit} \tag{4}$$

2. Defect per Opportunity (DPO)

$$DPO = \frac{Defect}{Unit\ \times\ Opportunities} \tag{5}$$

3. Defect per Million Opportunities (DPMO)

$$DPMO = DPO\ \times\ 1,000,000 \tag{6}$$

4. Sigma Level

$$\text{Sigma Level} = (((1,000,000 - \text{DPMO})/1,000,000) + 1.5) \tag{7}$$

Process improvements were designed and implemented in the "Do" stage, making a go/go jig, making a QR code scanner, and implementing 5S (Seiri (Sort), Seiso (Set in order), Seiton (Shine) , Setsuke (Standardize), Shitsuke (Sustain) in the jig fixture. The improvements were explicitly linked to sustainability drivers, barriers, and benefits under the Sustainability Awareness Model.

In the "Check" stage, the effectiveness of the interventions was evaluated by re-measuring process capability, Defects Per Million Opportunities (DPMO) values, sigma values, and Process Cycle Efficiency (PCE). Additionally, the Sustainable Value Stream Mapping (SVSM) and Process Activity Mapping (PAM) diagrams were updated to measure improvements in production flow, while Reduce, Reuse, and Recycle (3R) analysis was conducted to assess environmental impact reductions. Improvements were also assessed for their contributions to enhanced sustainability metrics associated with economic, social, and environmental elements.

The final "Action" stage involved standardizing the improved practice to avoid the recurrence of the same previously identified issues. By embedding the improved practices into standard operating procedures and aligning them with organizational goals in quality, cost, delivery, and environmental performance, we reinforced long-term sustainability. In summary, this methodology demonstrates how Lean Six Sigma tools, Sustainability Awareness, and Quality 4.0, utilizing decision trees CART Classification, and Power Business Intelligence in the heavy component manufacturing industry can be effectively applied to reduce waste, improve quality, and support the long-term viability of operations in the heavy equipment component manufacturing industry.

Figure 1 illustrates the research methodology flow using the Plan-Do-Check-Act cycle.

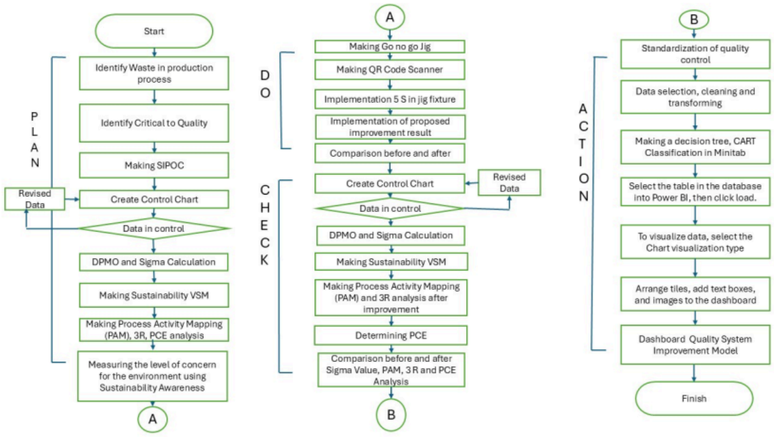

Figure 1 Research Methodology: Plan (Identify waste, identify CTQ, make SIPOC, create control chart, sigma calculation, make sustainability VSM, PAM, 3R, PCE analysis, and level concern of sustainability awareness); Do (Make go no go jig, make QR code scanner, implement 5S in jig fixture, and implement the proposed improvement result); Check (Create control chart, sigma calculation, make sustainability VSM, PAM, 3R, and PCE analysis and comparison before and after improvement); Action (Standardization of quality control, making decision tree CART classification, making dashboard quality system improvement model)

3. Results and Discussion

3.1 Plan stage

Six Sigma has helped organizations develop processes and product quality simultaneously to increase customer satisfaction and save company finances (Fitriana et al., 2021). In this study, product quality control at the company began when the raw materials used reached the production floor, where they were required to be packaged securely. The production process adhered to safety standards, with operators using appropriate protective gear and calibrated inspection tools. The personnel of the quality control division conducted routine inspections for each product before sending it to the following process to ensure that products conform to the company's standards. The company's quality standards are at Level 1, where there should be no defects when shipped. During the planning stage, a Supplier, Input, Process, Output, Customer (SIPOC) diagram was used to map and visually provide an overview of the production process. This facilitated the understanding and identification of the problem areas. Next, the critical-to-quality (CTQ) factors that affect customer satisfaction were identified. Analysis revealed 13 types of common defects: spatter, overlap, dangle, slag residue, fillet leg length, undercut, welding bead width not fitting, bead snaking, remaining groove, bead and dimensions unevenness, unequal center, incorrect size, penetration of welding, and cracking.

Statistical quality control was applied using a P-chart to monitor product variability. Statistical quality control monitors the production process, reduces product variability, maintains the products produced to meet predetermined standards, and avoids or reduces unnecessary waste (Montgomery, 2013).

The proportion of defects was obtained from 22 data points from observations. Based on the observations, 265 out of 650 products are defective, which make up the Bucket PC200. The control limits are then calculated for the P attribute control chart. The control limits contained in the P attribute control chart are calculated as follows:

$$CL = \bar{p} = \frac{265}{650} = 0.407$$

$$UCL = 0.4077 + 3\sqrt{\frac{0.4077(1 - 0.4077)}{31}} = 0.6725$$

$$LCL = 0.4077 - 3\sqrt{\frac{0.4077(1 - 0.4077)}{31}} = 0.1429$$

From this calculation, no data has crossed the control limits or is out of control. The graph on the plot results also shows that the proportion of defects from the production process is still within the control limits between the UCL and LCL values. The absence of out-of-control data indicates that each production process is still within the control limits, and the data should not be revised.

The DPMO and sigma levels are calculated to measure process performance. The following is the calculation of DPMO and sigma level for attribute data, where 650 products were inspected, 265 were defective, and 13 were opportunities. The DPU value is 0.4077, indicating a defect rate of 40.77% per product unit. Subsequently, the calculated DPMO value was 31,400, which corresponds to a sigma level of 3.361.

1. Defect per unit (DPU)

$$DPU = \frac{265}{650} = 0.4077$$

2. Defect per Opportunity (DPO)

$$DPO = 0.0314$$

3. Defect per Million Opportunities (DPMO)

$$DPMO = 0.0314 \times 1,000,000 = 31,400$$

4. Sigma Level

$$\text{Sigma Level} = (((1,000,000 - 31,400)/1,000,000) + 1.5) = 3.361$$

Although this result indicated that the process was of moderate to good quality, further improvement was needed, especially in alignment with sustainability goals concerning environmental, social, and economic impacts.

Sustainability awareness is a questionnaire that determines the level of awareness about the concept of sustainability in a company. This process is conducted by giving the questionnaire to several respondents, including experts in the production of Bucket PC200, and first explaining the concept of sustainability. The questionnaire contains general information about sustainability. It has several questions regarding sustainability drivers or driving and motivational factors, barriers or inhibiting factors, and benefits or benefits derived from implementing the concept of sustainability. Based on the results of completing the questionnaire, it can be seen that most of the factory's employees have heard of sustainability and are interested in the concept and its application to the company.

In this study, sustainable value stream mapping was used to add indicators from the previous value stream mapping methodology. Table 1 explains the sustainability indicators for sustainable value stream mapping, and the determination of indicators that refer to the three pillars of sustainability is obtained by looking at the company's conditions.

Table 1 Sustainability Indicators for Sustainable Value Stream Mapping

Category	Indicator	Source	Information
Economy E	Time (%)	(Hartini et al., 2021)	This study aims to identify value-added and non-value-added materials so that the period between incoming materials and finished products is known.
	Inventory (%)	(Marie et al., 2020)	Measure the effectiveness of inventory to balance customer demand.
	DPMO	(Delgadillo et al., 2022)	Knowing how well the production process works.
Social S	Satisfaction Level (%)	(Lestari et al., 2021)	Knowing the satisfaction level of workers in the company
	Noise level (%)	(Marie et al., 2020)	Noise level in the production process
	Safety Level (%)	(Hartini et al., 2021)	Percentage of employee reports for the number of risky activities from each workstation
	Employee training (%)	(Hartini et al., 2021)	The operator will give and carry out the training
Environment N	Material (%)	(Garbie, 2016)	Measuring the effectiveness of the material used during the production process
	Waste (%)	(Garbie, 2016)	Percentage of residual material used that will be recycled

There are indicators in making the SVSM, each with a different percentage value. This value is divided into three types using three traffic light colors, namely, red, yellow, and green, for the marker. The green color indicates a value following the specified target. Then, the yellow color indicates that the indicator can still be improved in achieving the company's target, while the red color means that the percentage value is still far below the company's target, so it is necessary to make improvements to achieve the company's target. Using sustainable value stream mapping, the production flow of the PC200 Bucket can be seen from start to finish. Based on the SVSM, the production process time is 2831.01 min, and the value-added time is 2341.6 min.

The study found that the company's increased market competitiveness was one of the driving forces behind its sustainability adoption. In contrast, the main barriers were the lack of infrastructure for implementing the waste treatment concept and employees' limited knowledge and understanding of sustainability. However, if a company applies this concept, benefits will be gained, one of which can improve the company's reputation and be recognized internationally. Implementing SVSM revealed key waste areas, such as product defects, overprocessing, motion, and waiting. Sustainability indicators on the three pillars were measured, such that the economic pillar itself was chosen based on the problems in companies related to cost savings to create solutions for economic growth and improve company quality. Social pillars are issues related to workers' conditions to obtain a better life and create systematic participation. Finally, the environmental pillar is related to environmental awareness.

Furthermore, PAM identification was carried out to classify operations into three categories: value added (VA), which is a process of adding value to the production process, and necessary non-value added (NNVA), which is a process that does not add value to products that will be generated, but it is necessary to do so. Finally, NVA is a process that does not need to be performed because it does not add value to the product to be produced. The total manufacturing lead time was 2831.01 min, with a process cycle efficiency of 82.71%. This indicated room for improvement, as most sustainability indicators fell within the 61%-90% range (yellow status). Approximately 63% of employees supported the implementation of sustainability practices to improve the company's capabilities.

Furthermore, an analysis was conducted using interrelationship and cause-and-effect diagrams to describe the interrelationships between problems so that the root causes of these problems could be obtained for improvement proposals. The results revealed key issues, such as extended inspection times, which led to defects, overprocessing, and delays. The proposed solutions included jig redesign, process map refinement, and the introduction of poka-yoke systems.

3.2 Do stage

The "Do" stage implemented the solutions based on the 5W + 1H and benefit-effort analyses. Suggestions for improvements included the manufacture of Go/No Go JIG tools to facilitate the manufacturing and inspection processes, PPO repairs to eliminate welding deformations, improvements to the drawing and JIG search system using a QR code scanner, and implementation of 5S (Sort, Set in order, Shine, Standardize, Sustain).

Figures 2 and 3 depict the proposed improvements, including the 5S display, Jig Go, and Jig Storage. Figures 2 (a) and (b) show the proposed 5 S Display Improvement and the poorly arranged components, which make the production floor messy. Figure 2 (c) is a picture after implementation, so it looks neater, and all the processed production results are arranged into one. This can also help keep the work environment clean and well-maintained.

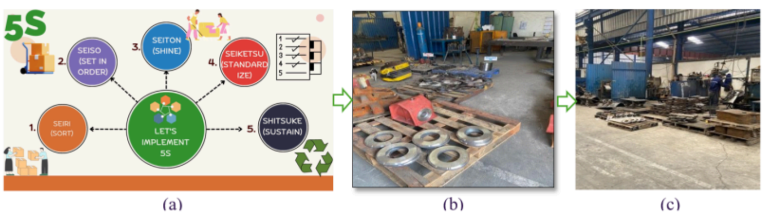

Figure 2 (a) Proposed 5S Display Improvements, (b) Before Improvement and (c) After Improvement

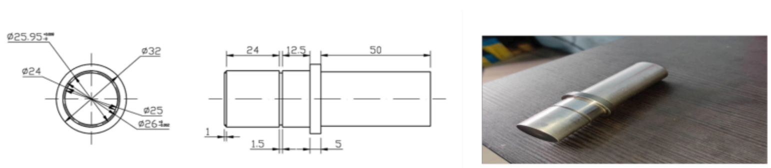

Figure 3 (a) Design of JIG Go/no-go and (b) proposed JIG Go

Figures 3 (a) and (b) show the designed Go/no-go JIG used by operators on the production floor as a checking tool and auxiliary tool in making products, so that the operator does not need to move to the laboratory and use a profile projector to carry out the inspection process.

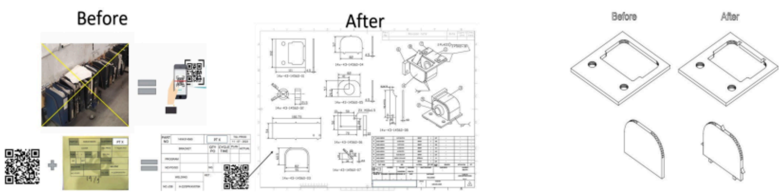

Figure 4 (a1) A work order is one of the outputs issued by PPIC to the production (section floor) to carry out production orders for each type of product to be produced; (a2) The application in which all images or drawings were converted into QR code forms; (a3) Drawings are included in the work order in the QR code; (b) Befoere addition of pin (b1); Poka-yoke addition of pins to the Bracket (b2)

The QR code scanner was introduced to reduce the time lost searching for numerous jigs and product drawings (Figure 4(a)). The PPIC operator then added the QR code images to the Work Orders. It can reduce the time spent searching for drawings, movement, and idle time during the welding process and avoid errors during the assembly process. The poka-yoke system was designed to ensure faster welding operations with a redesigned profile pattern that can prevent mistakes during the laser cutting process, as shown in Figure 4 (b).

(a) (b)

Figure 5 (a) Before: there is no cleaning welding tool; after: the proposed improvement is presented a routine cleaning for welding equipment; (b) Before: there is no work table and a place to put tools; after: finishing table Implementation

In Figure 5(a), before: there is no cleaning welding tool, after: the proposed improvement is a routine cleaning for welding equipment, which the company has approved for implementation. In Figure 5 (b), before: no table, after: the finishing table that has been made is installed in the lip-making process as a place to carry out the finishing process and to place tools such as grinders, reamers, MT, and others. This finishing table was designed to enhance operator comfort, improve production quality, and expedite product manufacturing.

3.3 Check stage

Based on this research, the proportion of defects obtained from 22 observed data after implementation was determined at PT X. Based on the results of observations, it is known that out of 101 products of the preparation of Bucket PC200, 634 are defective, from a production capacity of 634. The control limits are then calculated for the attribute P control chart. The control limits contained in the P attribute control chart after implementation are calculated as follows:

$$CL = \bar{p} = \frac{101}{634} = 0.1593$$

$$UCL = 0.1593 + 3\sqrt{\frac{0.1593(1-0.1593)}{32}} = 0.3534$$

$$LCL = 0.1593 - 3\sqrt{\frac{0.1593(1-0.1593)}{32}} = -0.0348 \approx 0$$

From these calculations, it can be concluded that no data have crossed the control limits or are out of control. Figure 8 shows the data plot of the P control chart calculation results after implementation. The plot image shows that the control limit line graph does not have a straight line shape due to the daily difference in UCL and LCL values daily.

Furthermore, the DPMO value and sigma level were calculated to measure the process performance. The following is the calculation of DPMO and sigma level on attribute data, where the number of products inspected is 634, the number of defective products is 101, and opportunities are 13.

1. Defect per unit (DPU)

$$DPU = \frac{101}{634} = 0.1593$$

2. Defect per Opportunity (DPO)

$$DPO = \frac{101}{634 \times 13} = 0.0123$$

3. Defect per Million Opportunities (DPMO)

$$DPMO = 0.0123 \times 1,000,000 = 12,300$$

4. Sigma Level

$$\text{Sigma Level} = (((1,000,000 - 12,300)/1,000,000) + 1.5) = 3.748$$

Table 2 Sample PAM Method and 3R Analysis (Reduce, Reuse, Recycle) After Implementation

No	Work Station	Activity Process		Cycle Time (minutes)	Activity Type					Categori			3R Analysis (Reduce, Reuse, Recycle)		
					O	T	I	S	D	VA	NVA	NNVA	R1	R2	R3
1	Welding and Machining Box	4	Chamber plate box	18.43	✓					18.43				✓	
		7	Finishing box	12.14	✓					12.14			✓		
		8	Inspection result of the machine of box	14.57			✓					14.57	✓		
2	Welding and Machining Lip	10	Champer plate lip	17.5	✓					17.5				✓	
		10	Finishing lip assy	250.11	✓					250.11			✓		
		10	Inspection result of the machine of lip	9.46			✓					9.46	✓		
3	Welding and Machining Ransel	22	Champer plate ransel	8.03	✓					8.03				✓	
		26	Radial drilling plate	2.03	✓					2.03				✓	
		30	Inspection result of the machine of Ransel	16.5			✓					16.5	✓		
4	Welding and Machining Bucket (Assembly)	36	Finishing Bucket	240.07	✓					240.07			✓		
		38	Inspection result of machining	33.6			✓					33.6	✓		
5	Painting and labelling	41	Inspection result of painting and labelling	5.11			✓					5.11	✓		
		42	Storage of products in the storage area with a forklift	3.48				✓			3.48				
Total category time (minutes)										2341.6	12.96	442.51			
Total Activity										25	4	13			
Time per shift (minutes)											480				
Manufacturing lead time (minutes)											2797.07				

D

Table 2 shows that the production process of the PC200 Bucket still has 5 workstations. However, after the implementation process, the number of processes was reduced to 42 activities, including 29 operation, 4 transportation, 8 inspection, and 1 storage activities. In the value analysis method (VAM), it is known that the processes that add and enhance the value of the product produced or categorized as value-adding (VA) have a total time of 2341.6 min. Next, in the non-value adding (NVA) category, which includes processes that do not add or enhance product value but need to be carried out to complete the production process, the total time is 442.51 min. Additionally, a category needs to be eliminated or reduced to increase the efficiency of the production process chain, with a total time of 12.96 min.

Based on the calculation results after implementation using process activity mapping, the manufacturing lead time or total production process time is 2797.07 min with a process cycle efficiency of 83.72%. Therefore, based on the results obtained, the process cycle efficiency has increased since the implementation process, indicating that the production process at Bucket PC200 can be more efficient after incorporating the concept of sustainability awareness into its improvements. The production process can also be considered good, as the higher the value, the more efficient the process, functioning at its maximum capacity. Thus, the application of the concept of sustainability awareness in the production process affects the economic, social, and environmental pillars.

In the 3R analysis after the company's implementation, the 3R activities that have been conducted are reduced and reused in the welding and machining processes as well as in the painting and labeling processes. For the process that has applied the concept of reduce, it is done by carrying out finishing and inspection processes so that if there are defects, they can be addressed beforehand to minimize the effort required for the repair process. Furthermore, the reuse concept is derived from the scrap obtained from the machining processes, namely chamfers and turning.

Before process repair, the sigma level value of the production was 3.361, and repairs were made to increase the sigma level value to 3.748, which means that there was an increase of 0.387 compared with the previous sigma level value. The DPMO decreased to 12,300 and the sigma level improved to 3.748. The PCE value increased to 83.72%.

The removal and combination of specific production steps caused variations in processing time, resulting in a more streamlined process flow. After improvements were implemented, a future state sustainable value stream mapping was developed to visualize the optimized production process. The new SVSM decreased the production process time to 2797.07 min, which increased the process cycle efficiency value (Figure 7). A 3R analysis was conducted as part of the post-implementation evaluation to assess the environmental aspects of the updated operations. Reduction activities were implemented in the finishing and inspection stages, allowing early detection and resolution of defects to minimize the energy and resources required for rework. Reuse initiatives were introduced by repurposing scrap materials from machining operations such as chamfering and turning. These efforts contributed to the more efficient use of raw materials. Additionally, the sustainable approach supported improvements in the recycling process, particularly within the painting and labeling stages, reinforcing the company's commitment to environmental sustainability.

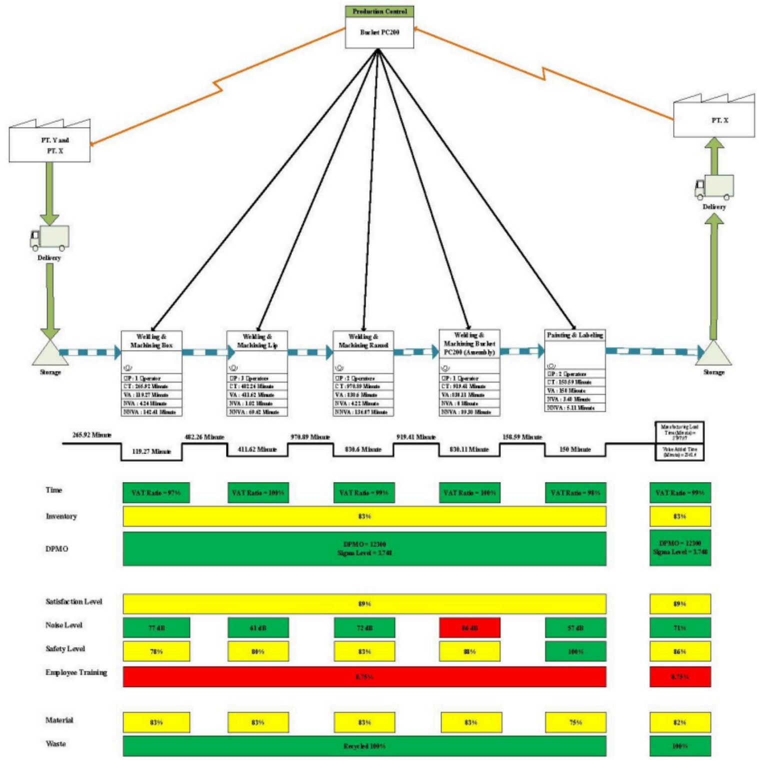

Figure 6 Mapping of the proposed sustainable value stream

3.4 Action Stage

The last "Action" stage involved standardizing and incorporating all successful improvements into QCP procedures. Continuous monitoring ensures consistent product quality.

At this stage, the next process must be carried out: maintaining the achieved quality control results so that the same problems do not occur and minimizing product defects in future production by setting new company standards. After several proposed improvements were implemented, it was discovered that the quality in the production process increased. The next stage evaluates the results of the improvements that have been implemented previously.

Table 3 Standardization of quality control

No	Causative factor	Normal company standards	Company Standard after Improvement
1	Many defects exist in the production	The company did not have a production floor predictive model	The company added a CART classification-based defect data model.
2	The emergence of waste, including defects, overprocessing, motion, and waiting	On the production floor, there are no information sources, such as displays, for operator knowledge.	The company sets up Visualization by PowerBI on the production floor as an integration of Quality 4.0 technologies for monitoring.
	The operator requires a jig as a checking tool.	The operator must move to the laboratory and use a profile projector to conduct the inspection process.	The designed Go/no-go JIG is used by operators on the production floor as a checking tool and auxiliary tool in making products, so that the operator does not need to move to the laboratory and use a profile projector to carry out the inspection process.
3	Time was lost searching for numerous jigs and product drawings.	Numerous jigs and product drawings are included in the paper.	All images or drawings were converted into QR code forms, and the PPIC operator added the QR code images to the Work Orders. The QR code scanner was introduced due to the time lost in searching for numerous jigs and product drawings.
4	Laser cutting is slow and has many errors	No poka-yoke system.	The poka-yoke system was designed with a redesigned profile pattern to ensure faster welding operations and avoid errors during the laser cutting process.
5	There is dirt on the welding equipment.	The company does not regularly set standards for cleaning and checking welding equipment.	The company performs a standard for cleaning and checking welding equipment after each production process.
6	Emergence of defects in product strength, quality, and appearance.	The company does not set proper standards for the finishing process of product production, and training for operators is only given when they start working for the company.	The company created worktables for the product production finishing process and trains operators at least once per year.

Based on the results of discussions with the company, the company was found to be able to implement the proposed improvements at the time of observation.

Adopting Quality 4.0, the decision tree CART classification model, and creating a dashboard with Power Intelligence, the company experienced measurable improvement in production quality. Figure 7 shows a decision tree and a CART classification from Minitab. The first node is split using the variable that records whether the production has a defect spatter; if yes, then it is repaired; if no, then it is accepted. There is no rejection in this case. Node 1 has 650 cases. Class Yes for terminal node 1 is 268 (41.2%), class No is 382 (58.8%). Node 2 contains cases where the defect undercuts, yes or no. If yes, means repaired, if no, means accepted. Node 2 class No has 588 cases. The "Yes" class for node 2 is 206, or 35%. The class "No" is 382, or 65%. The class "No" for node 2 is 62. The class 'Yes' is 62 or 100%. There are seven nodes of defect.

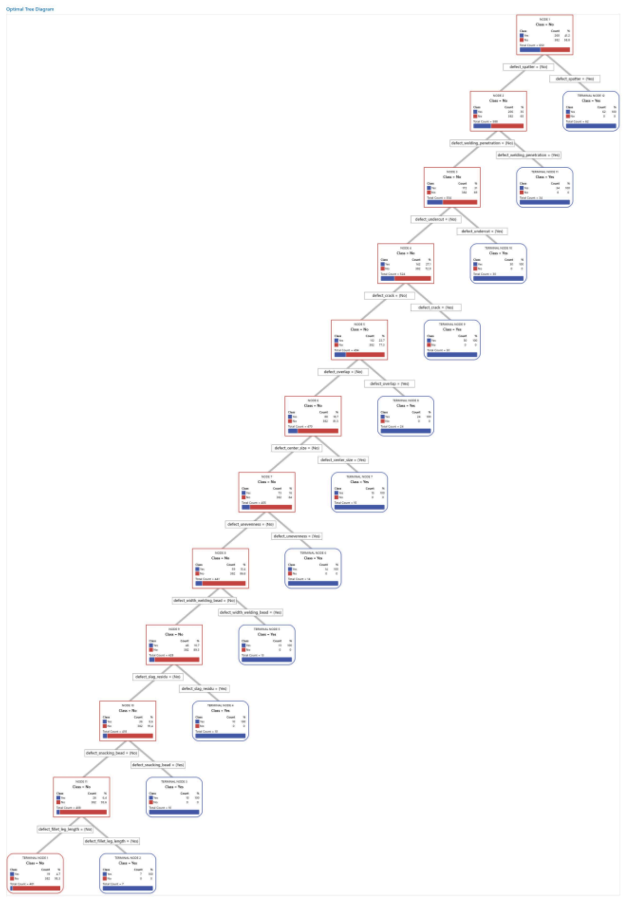

Figure 7 Decision Tree and CART Classification Chart

Figure 8 shows a visualization of quality improvement system with power business intelligence. This shows that the production capacity is 650. The total number of repairs was 211. Decisions are accepted 64.6%, and repairs are 35.4%. The sustainability VSM showed the green level: time VAT ratio of 99% Sigma Level of 3,748, a noise level 71%, an a material 82%, and a waste level of 100%. The green level: inventory level of 83%, satisfaction level of 89%, safety level of 86%, and material level of 82%. The red level is employee training at 8.75%. The comparison between the P Chart Before Implementation and the P Chart After Implementation. The sum of value added (VA) is 45.43%, non-VA (NVA) is 53.06%, and necessary non-VA (NNVA) is 1.51%. The highest relative variables were defect spatter (100%), defect cracks (78.9%), and defect overlap (72.9%). The ROC curve analyzed the area under the curve: training was 0.9646, and testing was 0.9520. Confusion Matrix analyzed predicted class (training) 92.9%, analyzed predicted class (testing) 92.9%.

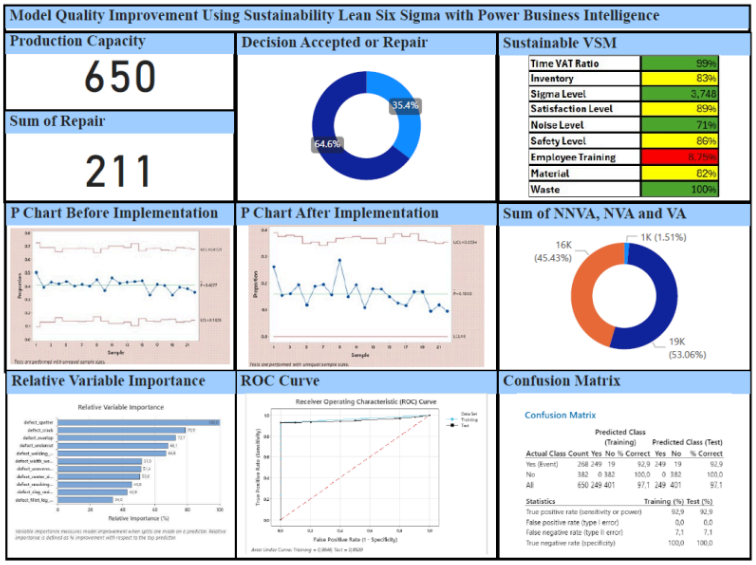

Figure 8 Dashboard Model Quality Improvement Using Sustainability Lean Six Sigma with Power Business Intelligence

4. Conclusions

This study explored how statistical process control, lean manufacturing, Six Sigma, quality 4.0, and sustainability can improve quality. Factors such as prolonged inspection time, welding deformation, drawing retrieval system unavailability, and production errors can affect production performance. The increase in sigma levels was evident after implementing the improvements. This improvement suggests that the implemented changes successfully improved the production process's quality and efficiency. Improvements were observed in the measurements of value-added, non-value-added, and manufacturing lead-time. Improvements in value-added, necessary non-value-added, and manufacturing lead time contributed to an increase in PCE. The proposed improvements included redesigning the jig, using QR code scanners, making a finishing table in the production process, regularly cleaning welding tools, creating a decision tree CART classification diagram, and creating a dashboard with Power Business Intelligence. Post-intervention analysis demonstrated an improved sigma level of 3.748 from 3.361. PCE increased from 82.71% to 83.72%. The results of the indicator values. The average sustainability category is in the yellow traffic light condition, namely 61% -90%, which means that this indicator can still be improved in achieving the company's targets, and the company can produce more efficient processes after implementing this concept. The results of this study have significant implications for quality improvement and sustainability in the production processes of heavy equipment component industries.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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