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Applications of Lean Manufacturing to Reduce Waste in the Crumb Rubber Industry

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ABSTRACT: This study focused on reducing waste in rubber powder production using Lean Manufacturing tools and improving process cycle efficiency. A quantitative case study was conducted at PT Perkebunan Nusantara IV Region 1, Gunung Para Plantation, North Sumatra, Indonesia. Waste was identified using the types-of-waste framework and ranked according to its impact on the production process. The selection of appropriate Lean tools was guided by Value Stream Mapping (VSM). The process was analyzed using Current Value Stream Mapping (CVSM), fishbone diagrams, and Future Value Stream Mapping (FVSM). The primary objective was to identify and reduce waste in the crumb rubber production process. The major types of waste identified were waiting time, excess inventory, product defects, and overprocessing. Based on the value stream analysis, several improvement strategies were proposed. The initial process cycle efficiency was 96.26%. After the proposed improvements were applied, particularly those aimed at reducing non-value-added time in the future value stream, process cycle efficiency increased by 1.82 percentage points to 98.08%. In addition, the production lead time decreased from 16,779.32 minutes to 16,467.93 minutes, representing a reduction of 311.39 minutes. The application of Lean Manufacturing and Value Stream Mapping effectively reduced production waste and improved the overall efficiency of the crumb rubber production process.

KEYWORDS: Crumb rubber; waste; lean manufacturing; value stream mapping; process cycle efficiency

1. Introduction

Indonesia is one of the world's leading producers of natural rubber and ranks second globally. In 2021, the value of Indonesia's rubber exports reached US$7.10 billion, accounting for approximately 3% of the country's total export value and representing a 26.42% increase compared with 2020 [1]. Natural rubber is one of Indonesia's major export commodities, alongside palm oil, coffee, and tea. In the global market, Indonesia is the second-largest exporter of natural rubber after Thailand, followed by Malaysia. Together, Thailand, Indonesia, and Malaysia account for nearly 70% of the global natural rubber market [2, 3]. Different rubber products require specific qualities and quantities of raw rubber; therefore, maintaining appropriate quality standards throughout processing is essential to ensure that final products meet industrial requirements and remain competitive in the global market [4].

Crumb rubber is produced through the mechanical processing of raw materials derived from the latex of *Hevea brasiliensis*, with or without additional chemical treatment. In Indonesia, crumb rubber quality is evaluated according to the specifications established by the Indonesian Rubber Standard (SIR) [5]. Minimizing waste during crumb rubber processing is therefore important for improving production efficiency and maintaining product quality. Lean Manufacturing provides a systematic approach to improving efficiency by identifying and eliminating waste throughout the production process [6]. Previous diagnostic research at PT Perkebunan Nusantara IV Regional 1, Gunung Para Plantation, identified approximately 58.19 metric tons of material losses resulting from inefficient production processes and product defects, particularly white spots and metal contamination. Of the 65,196 bales of crumb rubber produced, 2,388 bales contained white-spot defects and 1,217 bales were affected by metal contamination, resulting in products that did not comply with SIR requirements. Reducing these forms of waste could decrease production costs and work-in-process (WIP) inventory, improve resource utilization, and ultimately increase productivity [7]. Therefore, systematic identification and reduction of production waste are necessary to improve the overall performance of crumb rubber processing.

Value Stream Mapping (VSM) is a Lean Manufacturing tool used to distinguish value-added (VA) from non-value-added (NVA) activities throughout a production process. It provides a visual representation of material and information flows, enabling bottlenecks, unnecessary activities, excessive waiting times, and other sources of inefficiency to be systematically identified [8, 9]. By examining each stage of the production process, VSM can support smoother process flows, reduce waiting time, improve information transfer, and enhance overall process efficiency [9, 10]. Value-added time refers to the time spent on activities that directly contribute to transforming a product in a manner valued by the customer [11]. However, many previous studies have focused primarily on diagnosing production inefficiencies rather than developing practical improvement strategies that can be implemented within actual production systems.

Previous studies have demonstrated the effectiveness of Lean Manufacturing in reducing waste across various industrial sectors, including gear shaft manufacturing [12], the bottled-water industry [13], excavator manufacturing [14], the apparel industry [15], steel pipe manufacturing [16], the textile industry [17], rope manufacturing [18], and the automotive industry [19]. However, relatively few studies have investigated the systematic application of Lean Manufacturing to crumb rubber production. Moreover, limited attention has been given to integrating waste prioritization, appropriate Lean-tool selection, detailed process mapping, root-cause analysis, and measurable process improvements within a single framework for crumb rubber factories.

To address this research gap, the present study proposed a data-driven Lean Manufacturing framework integrating waste identification and prioritization, structured selection of Lean tools, Value Stream Mapping, and fishbone analysis. The framework was designed not only to diagnose production inefficiencies but also to develop practical and implementable improvement strategies for crumb rubber processing. Therefore, this study aimed to identify the major sources and root causes of waste and to reduce waiting time, unnecessary activities, and product defects in the crumb rubber production process. Current and Future Value Stream Mapping were applied to evaluate the existing production system and proposed improvements, with the overall objective of minimizing waste and improving process cycle efficiency.

2. Materials and Methods

2.1. Lean Manufacturing and Waste Identification.

Lean Manufacturing is a systematic approach to improving operational performance by reducing waste, minimizing inventory and production costs, and eliminating non-value-added (NVA) activities [20]. Manufacturing organizations continuously seek to improve their processes by distinguishing between value-added (VA) activities, which directly contribute to customer value, and NVA activities, which consume resources without increasing product value [21]. The fundamental objective of Lean Manufacturing is therefore to maximize customer value while minimizing unnecessary resource consumption. Although manufacturing systems are expected to operate efficiently, reliably, and with consistent product quality, various forms of waste frequently remain within production processes and provide opportunities for continuous improvement [18]. However, many previous Lean Manufacturing studies have primarily emphasized general waste-reduction outcomes, with limited operational guidance on how the identification and prioritization of dominant wastes can be translated into specific process redesign strategies. In Lean Manufacturing, waste refers to any activity that consumes resources but does not add value to the product from the customer's perspective [17]. Eight major categories of waste are commonly recognized: overproduction, waiting, inventory, transportation, unnecessary motion, defects, overprocessing, and underutilized employee skills [22]. Identifying these wastes enables organizations to determine the activities that contribute most significantly to production inefficiency. Nevertheless, improving individual activities without considering their relationships with upstream and downstream processes may disrupt the overall production flow. Therefore, waste reduction should be conducted from a value-stream perspective to ensure that improvements in one process do not create inefficiencies elsewhere in the production system [18].

2.2. Value Stream Mapping.

Value Stream Mapping (VSM) is a visual Lean Manufacturing tool used to represent the flow of materials and information throughout a production system. It facilitates the identification of VA and NVA activities while providing a comprehensive representation of actual process conditions [23]. By mapping process sequences, material movements, information flows, processing times, and waiting times, VSM enables bottlenecks and other sources of inefficiency to be systematically identified. This information can subsequently be used to develop targeted improvement strategies that reduce waste and enhance overall process efficiency [23]. VSM generally involves the development of a Current Value Stream Map (CVSM) and a Future Value Stream Map (FVSM). The CVSM represents the existing production conditions and identifies major sources of waste, whereas the FVSM illustrates the proposed production system after appropriate improvements have been introduced. Comparing these two conditions provides a basis for evaluating the potential effects of the proposed improvements on production flow and process efficiency. Because VSM is based on the visualization and analysis of process flows rather than on industry-specific characteristics, it can be applied across a wide range of manufacturing sectors [20].

2.3. Research Gap and Proposed Framework.

Crumb rubber production presents specific operational challenges because the characteristics and quality of incoming raw materials can vary considerably, while the final product must comply with established quality specifications. Production inefficiencies may also arise from product defects, such as white spots and contaminant residues, as well as limitations in drying capacity and space. These conditions can increase waiting time, generate unnecessary inventory, prolong production lead time, and contribute to defective products. Consequently, waste reduction in crumb rubber production requires an approach that considers both process efficiency and product-quality problems.

Previous research has demonstrated that Lean Manufacturing principles can be adapted to plantation-based and other manufacturing systems. Tools such as Current Value Stream Mapping (CVSM), fishbone diagrams, and Future Value Stream Mapping (FVSM) can support the identification of waiting time, process inefficiencies, and the root causes of product defects. However, previous studies have frequently applied individual Lean tools separately rather than integrating waste identification, waste prioritization, root-cause analysis, process redesign, and quantitative performance evaluation within a unified framework.

To address this gap, the present study proposed an integrated Lean Manufacturing framework consisting of three main stages: (1) visualization and diagnosis of the existing production process using CVSM, (2) identification of the root causes of dominant wastes using fishbone analysis, and (3) development of an improved production system using FVSM. The effectiveness of the proposed improvements was subsequently evaluated by comparing process cycle efficiency and production time before and after the proposed changes. This integrated approach provided a systematic link between waste identification, root-cause diagnosis, process redesign, and measurable improvements in crumb rubber production efficiency.

2.4. Research Design.

This study employed a descriptive quantitative case study design and was conducted at PT Perkebunan Nusantara IV Region 1, Gunung Para Plantation, North Sumatra Province, Indonesia. Data collection and direct observations were conducted from January to March 2026. During the study period, the factory had a production capacity of approximately 30 metric tons of crumb rubber per day. Primary data were obtained through direct observation of production activities, including process sequences, processing and waiting times, material flows, workstations, and operator involvement. These observations were used to characterize the existing production system and provide the input required for the development of the CVSM. Table 1 summarizes the workstations involved in the crumb rubber production process and the corresponding number of operators observed during the on-site assessment. These data provided the operational basis for identifying resource allocation and potential sources of inefficiency across the production stages.

Table 1. The Workstations and Operator Involved in the Production Facility.

No	Station	Number of Operator
1	Weighing	1
2	Loading ramp	1
3	Prebreaker	1
4	Blending	1
5	Hammermill	1
6	Crepper	3
7	Maturation	1
8	Shredder	1
9	Dryer	2
10	Pressing	2
11	Packaging	3
	Total	17

Table 1 presents the crumb rubber production line investigated in this study, from weighing to packaging. The rubber industry comprises upstream and downstream sectors, with the upstream sector processing plantation rubber into concentrated latex, ribbed smoked sheets (RSS), or technically specified rubber (TSR). Although TSR traditionally has a lower value than RSS, demand has increased because its block form facilitates handling and processing in tire manufacturing [3]. Based on previous diagnostic findings, this study applied Lean Manufacturing tools to identify and reduce waste and quantitatively evaluate the resulting improvements.

2.5. Research Flow.

The research framework consisted of nine integrated stages combining Lean Manufacturing tools with systematic process improvement, as illustrated in **Figure 1**. The stages included problem identification, formulation of research questions, data collection, Current Value Stream Mapping (CVSM), waste identification and prioritization, root-cause analysis, Future Value Stream Mapping (FVSM), and performance evaluation.

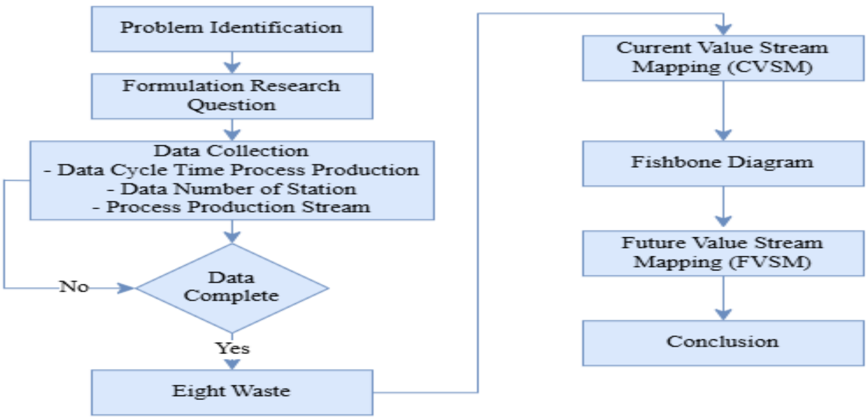

Figure 1. Research framework.

As shown in Figure 1, the study began with direct observations and informal interviews to identify inefficiencies in the crumb rubber production process. Waste was identified using a structured questionnaire based on the eight types of waste [24]. The dominant waste was then prioritized, with waiting time identified as the primary concern, consistent with previous diagnostic findings [25]. The existing process was analyzed using CVSM to classify activities as value-added (VA), necessary non-value-added (NNVA), or non-value-added (NVA), while also mapping material flows and waiting times [26]. A fishbone diagram was subsequently used to determine the root causes of the dominant waste [27]. Based on these findings, improvement strategies were developed and represented using FVSM. The effectiveness of the proposed improvements was then evaluated by comparing the current and future process performance.

2.6. Variables and Data Collection Procedures.

The study evaluated cycle time, normal time, and standard time as process variables, while types of waste and production output were used to assess production performance. Operational definitions were established to ensure consistent measurement and analysis of all variables [28, 29]. Data were collected at PT Perkebunan Nusantara IV Regional 1, Gunung Para Plantation through direct observation, interviews, literature review, and document review. Three observations were conducted for each of the 33 identified production activities. Each activity was classified as value-added (VA) if it directly contributed to customer value, non-value-added (NVA) if it provided no value and could be eliminated, or necessary non-value-added (NNVA) if it did not directly add value but was required to maintain production continuity [30].

2.8. Data Analysis Procedures.

The analysis focused on waste occurring throughout the crumb rubber production process, from the weighing to the packaging station. Lean Manufacturing analysis included cycle time, normal and standard time, manufacturing lead time, Process Cycle Efficiency (PCE), CVSM, FVSM, takt time, and fishbone analysis.

2.8.1. Cycle Time.

Cycle time (CT) is the time required to complete one production activity or work cycle. Reducing cycle time is an important Lean Manufacturing strategy for improving production responsiveness and operational efficiency [19, 31]. It was calculated as:

$$CT = \frac{\Sigma X}{n} \tag{1}$$

Where CT is the cycle time, Σx is the total observed processing time, and n is the number of observations.

2.8.2. Normal Time and Standard Time.

Normal time (NT) represents the time required for a worker to complete a task under normal working conditions. The Westinghouse method was used to determine the rating factor based on four criteria: skill, effort, working conditions, and consistency [17, 32]. Normal time was calculated as:

$$NT = CT \times (1 + RF) \tag{2}$$

Where NT is normal time, CT is cycle time, and RF is the rating factor.

Adjustment factors are determined using the Westinghouse method, which considers multiple performance aspects comprehensively and provides more accurate results. Normal time is then calculated using the Westinghouse rating factor to better represent actual working conditions [32]. The rating factor is evaluated based on four criteria skill, effort, working conditions and consistency. The scores of these factors are combined to determine the rating factor, which is then applied to the cycle time to obtain the normal and standard times.

Standard time is the time required for an average worker to complete a task under normal conditions, including allowances for rest, fatigue and unavoidable delays. It is established to determine the appropriate time needed to complete a specific task [33]. The formula uses is as follows:

$$\text{ST} = \text{NT x } \frac{100\%}{(100\% \text{ - Allowance})} \tag{3}$$

Where ST is standard time, NT is normal time and allowance is additional time allocated to workers to attend to personal needs.

2.8.3. Manufacturing Lead Time and Process Cycle Efficiency.

Manufacturing lead time is the total time required from the start of the process from the moment an order is received until the product is shipped to the customer [33]. Process Cycle Efficiency (PCE) measures production efficiency by comparing value added time with total production time. A PCE above 30% is generally considered an indication that lean principles have been effectively applied in the process [34]. The formula uses is as follows:

$$\text{PCE} = \frac{\text{Value Added Time}}{\text{Manufacturing Lead Time}} \text{ x } 100\% \tag{4}$$

Process Cycle Efficiency (PCE) evaluates production efficiency by relating valueadded time to the total production time. Value added time represents activities that directly enhance the product and satisfy customer needs, whereas manufacturing lead time covers the entire duration from receiving an order to delivering the finished product [35].

2.8.4. Current Value Stream Mapping and Future Value Stream Mapping.

CVSM was used to visualize the existing production process, evaluate process performance, and identify waste and improvement opportunities [17, 36]. FVSM was subsequently developed to represent the proposed improved process, including changes in processing and waiting times. Comparison of the current and future states provided the basis for evaluating the effectiveness of the proposed improvements.

2.8.5. Takt Time.

Takt time represents the required production rate needed to meet customer demand. It is determined by dividing the available production time by customer demand and can be used to balance production activities with the required output [23, 37]:

$$\text{Takt Time} = \frac{\text{Available minutes for production}}{\text{Required unites of production}} \tag{5}$$

Where takt time is determined based on the available working time and the number of units to be produced, total time available per month used to know time available in industry and customer demand per month used to supply customer demand per month.

2.8.6 Fishbone diagram

A fishbone, or cause-and-effect, diagram was used to systematically identify the root causes of the dominant production waste [38]. Potential causes were grouped into major categories, including man, machine, material, method, and environment, allowing the relationships between operational problems and their underlying causes to be systematically evaluated [39].

3. Results and Discussion

3.1. Lean Tool Selection Using Value Stream Mapping.

The production process was evaluated using cycle time, normal time, standard time, and manufacturing lead time. Based on Value Stream Mapping (VSM), activities were classified as Value Added (VA), Non-Value Added (NVA), or Necessary Non-Value Added (NNVA). VA activities directly contribute to product transformation and customer requirements, whereas NVA activities consume resources without adding value and should therefore be eliminated or minimized. NNVA activities do not directly add value but remain necessary for operational continuity [17]. The distribution of these activities and the resulting Process Cycle Efficiency (PCE), calculated using standard time, are presented in Table 2.

Table 2. Process Cycle Efficiency Based on Standard Time.

No	Activity Type	Quantity	Times (Minutes)	Percent (%)
1	Value Added (VA)	6	16,152	96.26
2	Non-Value Added (NVA)	4	319.57	1.9
3	Necessary Non-Value Added (NNVA)	23	307.75	1.84
	Total	33	16,779.32	100

As shown in Table 2, VA activities accounted for 16,152.00 minutes, or **96.26%** of the total production time, indicating that most processing time directly contributed to product transformation [15]. NVA activities accounted for 319.57 minutes (1.90%) and represented waste that could potentially be reduced or eliminated [40]. Meanwhile, NNVA activities accounted for 307.75 minutes (1.84%). Although these activities did not directly increase product value, they remained necessary for technical and operational requirements [7]. Therefore, the NVA and NNVA activities represented the primary opportunities for further improvement through Lean Manufacturing.

3.2. Waste Identification and Fishbone Diagram.

Waste identification was conducted using the eight-waste framework through a structured questionnaire involving operators and supervisors [24]. The responses were analyzed to prioritize the major sources of waste. The results identified waiting time, excess inventory, product defects, and overprocessing as the dominant wastes in the production system at PT Perkebunan Nusantara IV Gunung Para Plantation. A fishbone diagram was subsequently used to determine the root causes of these wastes, as presented in Figure 1.

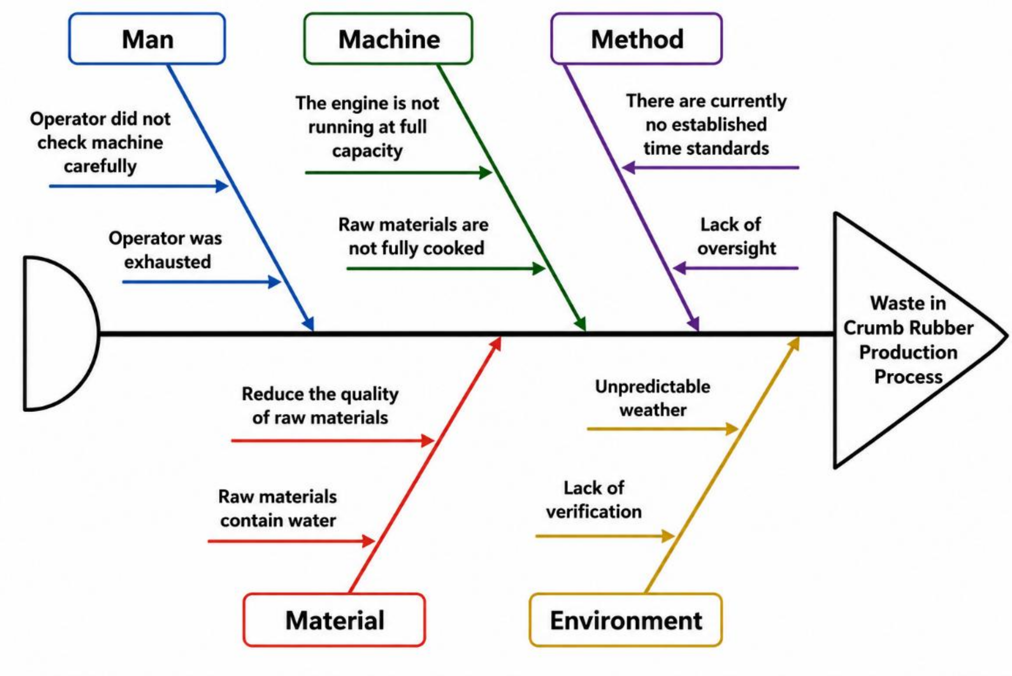

Figure 1. Fishbone Diagram Waste Identification.

As shown in Figure 1, five major factors contributed to production waste: unpredictable weather (environment), lack of established time standards (method), inadequate machine inspection by operators (man), machines operating below full capacity (machine), and declining raw material quality (material). These factors contributed to waiting time, unnecessary movement, transportation delays, and product defects. The fishbone analysis therefore indicated that waste resulted from interconnected operational, human, equipment, material, and environmental factors rather than from a single production activity [39].

3.3. Current value stream mapping

The data used for Current Value Stream Mapping (CVSM) included cycle time, normal time, standard time, and manufacturing lead time. Value-added (VA) activities were defined as activities that directly transformed the product and contributed to meeting customer requirements. Value Stream Mapping (VSM) was used to visualize the entire production flow, including both value-added and non-value-added activities, from the receipt of raw materials to the final product [41]. Based on direct observations and field assessments, the crumb rubber production process was not operating optimally because several activities did not fully comply with the operational standards commonly applied in the industry. The CVSM was therefore developed to represent the existing production conditions, including material flow, processing time, waiting time, and other sources of inefficiency. This mapping provided a baseline for identifying improvement opportunities and developing the future-state production process. The existing crumb rubber production flow is presented in Figure 2.

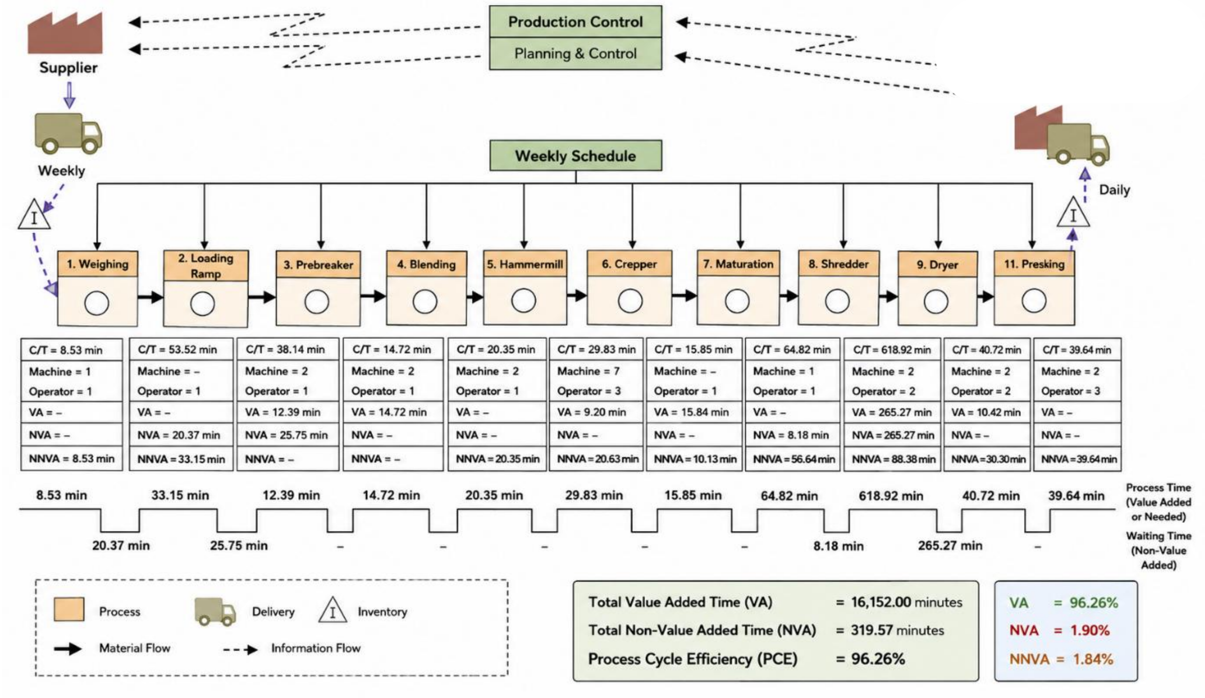

Figure 2. Current value stream mapping

Based on the Value Stream Mapping (VSM) results presented in Figure 2, several major sources of waste were identified in the crumb rubber production process, including waiting time, excess inventory, product defects, and overprocessing. These wastes were further analyzed to identify their underlying causes and determine appropriate improvement priorities. Based on the identified causes, improvement strategies were developed for the five major categories of man, method, machine, material, and environment, as summarized in Table 3.

Table 3. Proposed Improvements for Identified Sources of Waste.

Category	Proposed Improvement
Man	Selecting qualified employees in their respective fields and conduct evaluations to ensure compliance with regulations
Method	Improvement of work control factors
Machine	Performing regular engine maintenance and improvements in machine
Material	Conduct inspections to ensure compliance with standards, conducting material inspections and performing a check on the shredder
Environment	Move it to a suitable location

As shown in Table 3, the proposed improvements addressed the root causes identified in the production process rather than focusing only on individual waste events. Improvements related to operators and work methods emphasized competency, monitoring, and standardized procedures, while machine-related improvements focused on preventive maintenance and inspection. Material controls were proposed to prevent unsuitable raw materials from entering subsequent processing stages, whereas environmental improvements focused on providing adequate production and storage space. Collectively, these measures were expected to reduce waiting time, inventory accumulation, defects, and unnecessary reprocessing.

Waiting time was primarily observed at the loading ramp, prebreaker, and dryer stations. At the loading ramp, raw materials waited 20.37 minutes before unloading, while the prebreaker station recorded 25.75 minutes of waiting before processing. At the dryer station, an initial waiting time of 8.18 minutes occurred before drying, followed by 265.27 minutes while the crumb rubber cake underwent the drying process. These delays interrupted production flow and represented important opportunities for reducing non-value-added time.

Excess inventory mainly occurred at the loading ramp and maturation areas. At the loading ramp, raw materials accumulated while waiting to enter the production process. Additional accumulation occurred at the maturation station because rubber blankets had to be stored for at least 11 days before subsequent processing, while the available storage space was limited. This imbalance between material inflow, processing capacity, and storage availability contributed to work-in-process accumulation and inefficient material flow.

Product defects were mainly associated with the shredder and dryer stations. At the shredder station, oversized or excessively thick crumb rubber pieces were produced because of inadequate shredding and variations in the homogeneity and moisture content of the matured rubber blankets. At the dryer station, incomplete drying and unstable operating temperatures resulted in under-cured or insufficiently dried products. Field observations showed that, of 65,196 bales produced, 2,388 bales contained white-spot defects and 1,217 bales contained metal contamination, resulting in products that did not meet the required quality standards.

Overprocessing was closely associated with these product defects. Crumb rubber containing excessive white spots or metal contamination could not proceed as a conforming final product and therefore required additional processing or reprocessing to meet the required standards. This repeated processing increased production time and resource consumption without adding value to the product. Consequently, controlling defects at their source was important not only for improving product quality but also for reducing overprocessing and improving overall process efficiency.

3.3. Future Value Stream Mapping.

Based on the proposed improvements, the production process was re-evaluated using cycle time, normal time, standard time, and manufacturing lead time. Activities were classified as Value Added (VA), Non-Value Added (NVA), and Necessary Non-Value Added (NNVA) to evaluate the expected improvement in production efficiency. The proposed Process Cycle Efficiency (PCE), calculated based on standard time, is presented in Table 4.

Table 4. Proposed Process Cycle Efficiency Based on Standard Time.

No	Activity Type	Quantity	Times (Minutes)	Percent (%)
1	Value Added (VA)	6	16,152	98.08
2	Non-Value Added (NVA)	1	8.18	0.01
3	Necessary Non-Value Added (NNVA)	23	307.75	0.2
	Total	**30**	**16,467.93**	**100**

As shown in Table 4, the proposed production system maintained the VA time at 16,152.00 minutes, representing 98.08% of the total production time. These activities directly transformed the product according to customer requirements [15]. Following the proposed improvements, NVA time was reduced to only 8.18 minutes (0.05%), indicating a substantial reduction in activities that did not contribute value to the product [40]. Meanwhile, NNVA activities accounted for 307.75 minutes (1.87%). Although these activities did not directly add product value, they remained necessary for technical and operational requirements [7].

Compared with the current condition in Table 2, the proposed improvements reduced the total production time from 16,779.32 to 16,467.93 minutes, corresponding to a reduction of 311.39 minutes. At the same time, PCE increased from 96.26% to 98.08%, representing an improvement of 1.82 percentage points. This improvement was primarily achieved by reducing NVA time while maintaining the required VA and NNVA activities. The resulting improved production flow and proposed operating conditions are illustrated in the Future Value Stream Mapping (FVSM) presented in Figure 3.

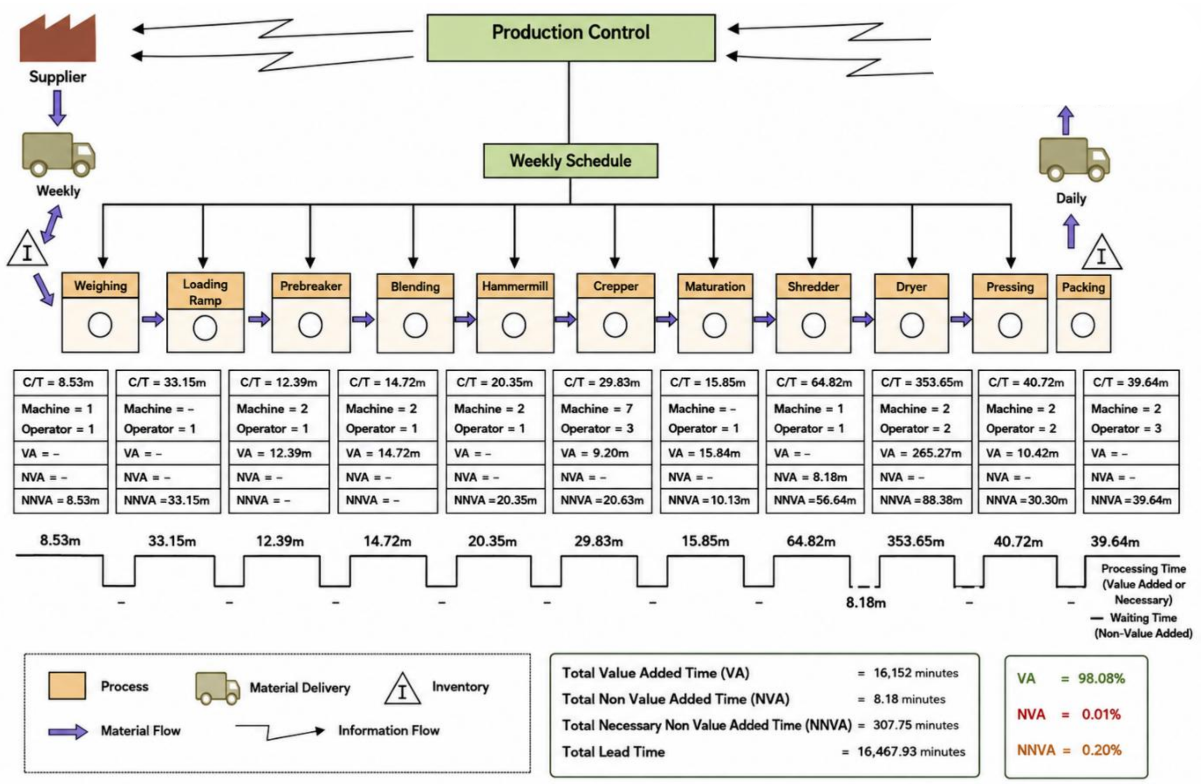

Figure 3 . Future value stream mapping.

Based on the mapping results presented in Figure 3, waiting time was reduced at several workstations compared with the initial conditions. The waiting time between the weighing and loading ramp stations was reduced by 20.37 minutes, while that between the loading ramp and prebreaker stations was reduced by 25.75 minutes. The largest reduction occurred between the dryer and pressing stations, where waiting time decreased by 265.27 minutes. Overall, these reductions demonstrate that non-value-added activities, particularly waiting time, could be substantially minimized through the proposed process improvements [41]. A comparison between the current and proposed value streams is presented in Table 5.

Table 5. Comparison of the Current and Proposed Value Streams.

No	Activity Type	Actual	Proposed	Gap
1	Value Added (Minutes)	16,152	16,152	-
2	Non-Value Added (Minutes)	319.57	8.18	311.39
3	Necessary Non-Value Added (Minutes)	307.75	307.75	-
4	Manufacturing Lead Time (Minutes)	16,779.32	16,467.93	311.39
5	Process Cycle Efficiency (%)	96.26	98.08	1.82

As shown in Table 5, the proposed improvements reduced NVA time from 319.57 to 8.18 minutes, representing a reduction of 311.39 minutes. Consequently, manufacturing lead time decreased from 16,779.32 to 16,467.93 minutes, while VA and NNVA times remained unchanged. Process Cycle Efficiency (PCE) increased from 96.26% in the current state to 98.08% in the proposed state, representing an improvement of 1.82 percentage points. These results indicate that the proposed changes improved overall production efficiency primarily by eliminating unnecessary waiting time. PCE and takt time provide quantitative indicators that complement VSM by evaluating the proportion of value-added time within the total lead time and aligning the production rate with customer demand [42].

3.4. Discussion.

The Current Value Stream Mapping (CVSM) showed a PCE of 96.26%, indicating that although most production time was value-added, opportunities remained to reduce NVA activities, particularly waiting time. Such activities consume production time and resources without directly contributing to product value and can therefore reduce overall process efficiency [17]. Similar improvements through Lean Manufacturing have been reported in previous research [18], where processing and waiting times were reduced by approximately 68% and 88%, respectively, and total order-to-dispatch time decreased from 36 to 9 days. These findings demonstrate the importance of reducing both processing inefficiencies and waiting time to improve overall production flow.

Following waste identification and root-cause analysis, targeted improvements were proposed to minimize or eliminate the identified sources of waste [7]. The improved process was subsequently represented using Future Value Stream Mapping (FVSM). The proposed future state reduced NVA time by 311.39 minutes and increased PCE from 96.26% to 98.08%, corresponding to an improvement of 1.82 percentage points. Importantly, this improvement was achieved without changing the total VA time, indicating that the efficiency gain resulted primarily from reducing unnecessary activities rather than altering the core production operations.

The reduction in NVA time also demonstrates the practical importance of integrating VSM with waste identification and root-cause analysis. Rather than merely identifying inefficient activities, the proposed framework linked the dominant wastes to specific operational improvements involving workers, methods, machines, materials, and the production environment. This approach enabled improvement measures to be directed toward the underlying causes of waiting time, excess inventory, defects, and overprocessing.

Overall, the FVSM results indicate that Lean Manufacturing could improve crumb rubber production by reducing unnecessary waiting time, improving material flow, and increasing the proportion of productive time within the overall process. Although the increase in PCE was relatively modest at 1.82 percentage points, the corresponding reduction of 311.39 minutes in manufacturing lead time represents a meaningful operational improvement. These findings support the application of an integrated Lean Manufacturing approach as a practical strategy for improving efficiency and minimizing waste in crumb rubber production.

4. Conclusions

This study demonstrated the effectiveness of Lean Manufacturing in identifying and reducing waste in the crumb rubber production process at PT Perkebunan Nusantara IV Regional 1, Gunung Para Plantation. The major sources of waste were identified as waiting time, excess inventory, product defects, and overprocessing. Current Value Stream Mapping (CVSM) showed a manufacturing lead time of 16,779.32 minutes and a Process Cycle Efficiency (PCE) of 96.26%. Based on waste prioritization and root-cause analysis, targeted improvements were proposed and incorporated into the Future Value Stream Mapping (FVSM). The proposed future state reduced manufacturing lead time to 16,467.93 minutes by eliminating 311.39

minutes of non-value-added time, while increasing PCE to 98.08%, an improvement of 1.82 percentage points. These findings demonstrate that integrating value stream mapping, waste identification, and root-cause analysis provides a practical approach for improving production flow, minimizing unnecessary activities, and enhancing the operational efficiency of crumb rubber production.

Acknowledgments

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Author Contribution

Defi Irwansyah: conceptualization, methodology, supervision, writing and review. Diana Khairani Sofyan: methodology, data analysis, supervision, writing, and review. Muhammad Ashraff: conceptualization, methodology, data collection, data analysis, writing and visualization.

Competing Interest

The authors declare that they have no competing interest regarding on the publication in this paper.

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