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# Lean Manufacturing through VSM and SMED for Waste Reduction in Paper-Based Packaging

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**Abstract**. This study analyzes the reasons for waste in the production processes of a paper-based food packaging company in Indonesia and proposes improvement measures to make the operations more efficient. Through the application of Value Stream Mapping (VSM) and Single-Minute Exchange of Dies (SMED), three significant waste categories were charted: product defects (24.74%), unnecessary movements (22.23%), and unnecessary inventory (13.29%). Implementation of SMED successfully reduced the time of tool change from 60.24 minutes to 27.12 minutes, a setup time improvement of 54.98%. Pursuit of labeling system improvement as well as putting in place a Just-In-Time (JIT) inventory practice also played an important role in the reduction of wastes and fast responsiveness. Consequently, Process Cycle Efficiency (PCE) increased from 70.37% to 73.41%, production capacity increased by 1,241 units per cycle, and complaint counts for defective products declined appreciably over a period of six months. These results underscore the actual benefits of Lean methods and underscore the standard for performance excellence for the same pursuit of sustainable operational excellence within the same industry.

**Keywords**: Lean Manufacturing, VSM, SMED, PCE, paper food packaging, waste assessment model, process cycle efficiency and operational waste.

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## 1. Introduction

Global concern regarding the environment, especially plastic waste management, has increased significantly during the past decade. Indonesia, being recorded as a prime mover of plastic pollution, responded by launching regulatory measures, in the form of Ministerial Regulation No. 75 of 2019, requesting a prohibition on single-use plastics nationwide by 2030. Such regulation has driven the development of more eco-friendly alternatives to which paper-based food and beverage packaging is prominent. As argued by Tun et al. (2023), compliance with regulations across Southeast Asia has been a pivotal driver in propelling industrial changes towards the utilization of biodegradable packing with both environmental and economical advantages [1].

But with great heralded market opportunities, the Indonesian paper packaging company has experienced dramatic fluctuations in its bottom line performance [2]. Between the periods of January and May 2024, the company's financial performances recorded its profit and loss margins swinging wildly in between 2%, -1%, 4%, -2%, and -7%, respectively. The volatility is accompanied by the possibility of compromising the long-term sustainability of the company if left addressed. The preliminary review of the accounts reveals that product faults have led to direct financial losses due to customer complaints. The company has been forced to rework faulty products due to these complaints, resulting in massive wastage of time, material, and labour. The cost of rejected items as of June 2024 has been over IDR 100,000,000, reflecting the critical need for an overall view of the operational processes for process optimization and reduction of inefficiencies [3].

The objective of the study is to carry out a detailed examination of the production process to determine where there are wastes and inefficiencies that negatively impact financial performance as well as operational efficiency. Lean Manufacturing methodologies, specifically Value Stream Mapping (VSM) and Single-Minute Exchange of Dies (SMED), have proven to be effective in reducing waste and maximizing productivity [4]. Previous studies in other sectors, i.e., the automotive and bakery sectors, have established that Lean Manufacturing significantly reduces processes that do not add value and optimizes total production efficiency. For instance, more recent studies by Alanya et al. (2024) in textile and Peña & Veliz (2024) in baking production highlight the universal benefits of implementing Lean tools in process simplification and reducing setup times [5] [6]. However, literature is still shallow in the area of exploration of the application of such tools to the paper-based packaging business sector with its unique operation issues such as raw material deterioration and high-speed production runs. This study tries to fill this gap by exploring the application of VSM and SMED in the paper packaging industry in Indonesia with a focus on waste identification and operation improvement.

Previous studies have widely investigated the application of Lean Manufacturing techniques, i.e., Value Stream Mapping (VSM) and Single-Minute Exchange of Dies (SMED), to various manufacturing sectors with a view to minimizing waste and maximizing productivity. Empirical evidence shows the effectiveness of Lean philosophy in the textile industry, leading to high rise in process flow and manufacturing ability [5]. Equally, implementation of SMED and VSM in bakery processes has been found to cut significantly into setup time and increase operational performance [6]. Other studies have highlighted the value of VSM in pinpointing bottlenecks in automobile manufacturing lines, thus facilitating continuous process enhancement [7]. However, evidence also indicates that introduction of SMED is industry-specific and hence is subject to variation based on the limitations of the sector [8]. Despite these developments, the application of these methodologies in the paper-based packaging sector remains unknown, even more so in light of its unique challenges, such as raw material degradation and high-speed production demands. This study seeks to bridge such knowledge gap by focusing on the implementation of Lean Manufacturing for the paper-based food packaging sector. Furthermore, more research is required to ascertain the long-term sustainability and performance of such improvements over extended periods of operation.

This research gap will be addressed within this study through the implementation of Lean Manufacturing concepts of Value Stream Mapping (VSM) and Single-Minute Exchange of Dies (SMED) in a paper food-packaging company. The primary aim is to identify the reasons for waste in production and suggest the most efficient strategies that maximize operation, reduce the production cost, and enhance the financial return of the firm. The findings of this research are expected to be of greater benefit to the stakeholders and also help develop environmentally friendly practices within the packaging industry in line with Indonesia's stricter environmental laws.

## 2. **Methods**

In this study, Lean Manufacturing fundamentals are utilized, giving emphasis to Value Stream Mapping (VSM) and Single-Minute Exchange of Dies (SMED). VSM is utilized to visually map the production process such that value-added and non-value-added activities are viewed, and Process Cycle Efficiency (PCE) calculation is performed. PCE is a key metric of manufacturing efficiency in terms of relating value-added operation time to the whole cycle time. At the same time, SMED is employed to minimize setup time by distinguishing between internal and external setup operations in an effort to enhance responsiveness and overall productivity [10].

In addition to these Lean tools, the Waste Assessment Model (WAM) was employed in an effort to describe waste types and assess their relative contribution. WAM employs a Waste Relationship Matrix (WRM) and an intrinsic scoring system. It was evaluated by five industrial engineering experts with work and academic experience, all having over five years of experience in Lean implementation. They were provided with observation data and facilitated questionnaires to quantify all types of waste on two dimensions: urgency and effect, both having scores on a five-point scale. The scores that were produced were added and averaged to give the most critical waste types.

Experts were prompted on the WAM questionnaire to rate each of the categories of waste on the following scales: (1) Urgency—how much the waste erodes short-term operational stability (1 = low urgency, 5 = very urgent), and (2) Impact—the degree of performance degradation caused by the waste (1 = small impact, 5 = high impact). Data collection was done through formal interviews and written score sheets. The individual rating of each expert was independent, with the average scores later used to rank the wastes identified. As a matter of transparency and reference, expert ratings are presented in Table 1.

**Tabel 1.** WAM Expert Judgment Summary

| **Waste Type** | **Average Urgency Score (1–5)** | **Average Impact Score (1–5)** | **Weighted Score (Urgency × Impact)** |
|---|---|---|---|
| Product Defects | 4.8 | 5.0 | 24.0 |
| Unnecessary Motion | 4.3 | 4.4 | 18.9 |
| Excess Inventory | 3.9 | 3.5 | 13.7 |
| Overproduction | 2.7 | 2.9 | 7.8 |
| Waiting Time | 2.4 | 2.6 | 6.2 |
| Transportation | 2.0 | 2.5 | 5.0 |

Note: Scores are averaged from 5 experts across academia and industry.

In order to avoid inconsistency and subjectivity of the expert judgments, inter-rater reliability was established by using Cohen's Kappa and achieving a value of 0.81, representing very high agreement between raters. Application of multiple experts and ordered appraisal rubrics ensured validity and reliability of the findings. Ethical clearance for expert participation was sourced from internal approval mechanisms, and that the informed consent of all participants prior to their involvement in the evaluation process had been secured.

The data utilized in the study were collected by means of direct observation in the field, semi-structured interviews, and company documentation using various tools. The outputs derived from the Waste Assessment Model (WAM) and Waste Relationship Matrix (WRM) were also analyzed using a Fishbone Diagram to identify the root causes of the inefficiencies. Process Cycle Efficiency (PCE) was evaluated pre- and post-intervention using the formula.

The formula to calculate PCE is as follows:

$$PCE = \frac{Time\ for\ value\ adding\ activities}{Total\ Cycle\ Time} \times 100\% \quad (1)$$

Methodologically, the procedure also comprised pre- and post-assessment of SMED deployment on setup time and changeover efficiency. Data was gathered for three months

(March–May 2024) while performing the baseline measurement, implementation of the intervention, and monitoring phases in a systematic sequence.

### 2.1. *Analysis with Waste Assessment Model (WAM)*

Production records and company financial accounts were the most important determinants in the exploration of performance variability in this study. Value Stream Mapping (VSM) and time measuring were executed by utilizing computer applications to perform the Process Cycle Efficiency (PCE) and setup time [11]. Furthermore, a SMED system was implemented in the production machinery to accelerate changeover operations and reduce setup time [12].

Waste Assessment Model (WAM) was also applied to contrast waste categories and relate with manufacturing tools through the Waste Relationship Matrix and Waste Assessment Questionnaire. This helped in recognizing and reducing the existing wastes that lead to inefficiencies in processes on time. The techniques employed included expert-instructed questionnaires and interviews to ascertain the priority and power of the recognized wastes, which were initially laid down by the Fishbone Diagram. Setup time waste was specifically analyzed and addressed through the implementation of SMED, aimed at optimizing and shortening preparation durations [13].

### 2.2. *Future Value Stream Mapping Design*

Following the design of improvement plans—mainly through the application of Lean tools such as SMED for more efficiency, effectiveness, and optimization of the process—the second was to design a Future State Value Stream Map (VSM) [14]. The PCE value prior to improvement was then assessed and quantified against the predicted PCE value following the application of the proposed enhancement.

Methodological design initiated by mapping the process of production with VSM to identify inefficiencies and calculate Process Cycle Efficiency (PCE). This was followed by a WAM analysis to group and analyze wastes. This was followed by SMED to reduce setup time and increase overall production efficiency [15]. Pre- and post-intervention comparisons of PCE were carried out to identify the impact of improvements. All steps of the study were carried out with great diligence so that results could be implemented practically within the organization and help create long-term industrial sustainability plans.

## 3. **Result and Discussion**

### 3.1. *Identification of Value-Added and Non-Value-Added Time through Value Stream Mapping (VSM)*

The Lean Manufacturing enhancements—a synthesis of SMED, improved labeling, layout streamlining, and a Just-In-Time (JIT) system—were implemented over a period of three months from March to May 2024. The reforms were rolled out incrementally and monitored on a weekly basis by in-house performance audits. Key performance indicators like setup time, defect rate, and inventory turnover were routinely collected using standard checklists by the production supervisor team. A Gantt chart was used to plan, execute, and evaluate each phase of the intervention. Value Stream Mapping (VSM) was employed in the mapping of the informational as well as physical flows of the production system. The outcome of the mapping was a total cycle time of 800.61 minutes to manufacture 30,000 units of the SW 12 oz Paper Cup, which included 563.40 minutes of value-added and 237.20 minutes of non-value-added activities.

- “Cycle Time per unit = 0.0267 minutes/pcs
- Take Time (based on customer demand of 1,000,000 pcs/month) = 0.0216 minutes/pcs

The current state mapping is shown in Figure 2. Current State VSM

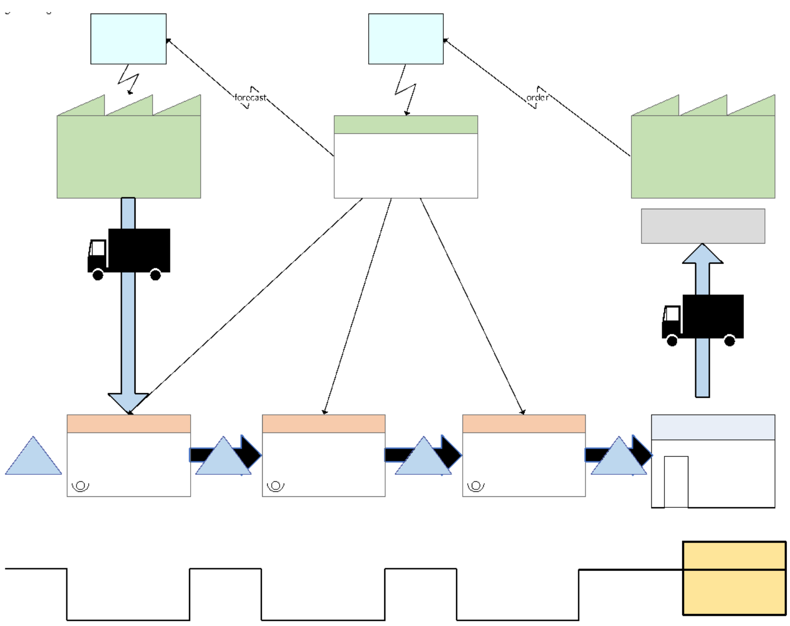


**Figure 1.** Determining the current Process Cycle Efficiency (PCE)

3.2. *Determining of Process Cycle Efficiency (PCE) before Improvement*

The initial Process Cycle Efficiency (PCE) prior to the intervention was established and is presented in Figure 1. The PCE was at 70.37% prior to the introduction of the Lean Manufacturing interventions. It increased to 73.41% after the intervention, as noted in Figure 1.

3.3. *Analysis of Waste and Relatedness using Waste Assessment Model (WAM)*

Table 2 shows the three most common forms of waste that were found to significantly hinder production efficiency, as identified by the Waste Assessment Matrix (WAM) and Waste Relationship Matrix (WRM).

**Table 2.** Waste in the Production Process

| | |
|---|---|
| Defect | 24.74% |
| Unnecessary Motion | 22.23% |
| Excess Inventory | 13.29% |

The WRM explains how one form of waste can exacerbate others. For instance, overstocking generates excess motion through inefficiently searching for and managing materials by workers.

Through the application of the WAM and WRM, it was determined that the three most detrimental forms of waste to production efficiency are product defects (24.74%), unnecessary motion (22.23%), and excess inventory (13.29%). The WRM highlights the interdependencies among various types of waste, demonstrating that surplus inventory necessitates additional, inefficient movement in material handling.

*3.4. Root Cause Analysis of Waste using a Fishbone Diagram*

According to the Waste Assessment Matrix (WAM), these three primary categories of waste that most contribute to inhibiting production effectiveness are defects (defective products) with 24.74%, unnecessary motion with 22.23%, and excess inventory with 13.29%.

### 3.5. *Defect Wastage Analysis*

The most prevalent category of waste discovered in this study is defective products with 24.74% of the overall waste. From the Fishbone Diagram analysis (Figure 3), the root causes of defects in the production of 12 oz SW Paper Cups are operator errors in ink setting adjustments, thermal fluctuations, and the lack of a raw material labeling system. A common issue experienced is ink blockage, commonly due to print misalignment caused by the absence of position indicators on paper rolls. These underlying causes are pictorially represented in the Fishbone Diagram of Figure 2.

In order to correct these issues, an improved labeling system was implemented on paper rolls so that operators can easily identify regions where there is ink blockage [16], [17]. In addition, operator training was conducted to enhance skills and knowledge in managing key parameters of production, such as heating temperature, before production started. All these enhancements were the cause of the reduction of customer complaints regarding defects, as indicated by Figures 2 and 3.

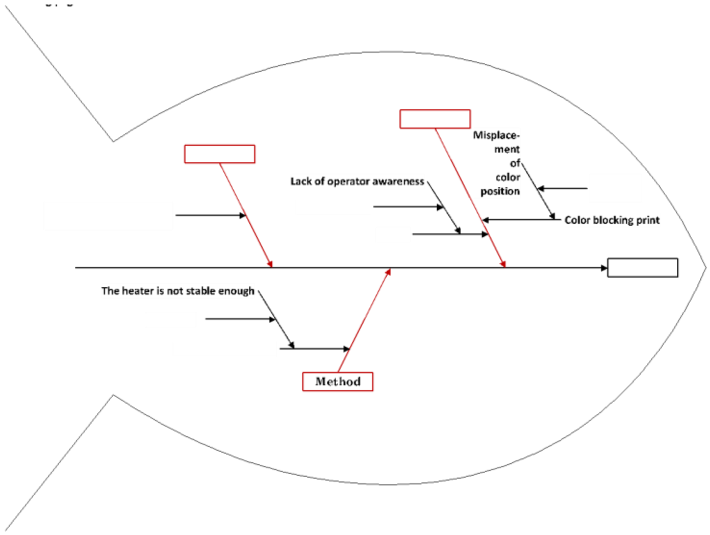


**Figure 2.** Fishbone for Defect Wastage

### 3.6. *Unnecessary Motion Waste Analysis*

Waste caused by unnecessary motion, which accounts for 22.23%, is caused by improper workstation design, excessive accumulation of materials around the work area, and longer tooling changeover. Figure 3 indicates the causes of this waste type. It is observed that inefficient operator movement is typically caused by congested working conditions caused by unremoved materials. In addition, tooling changeover time for the punching operation generates productive time losses.

To address this, SMED methodology was applied to accelerate the tooling changeover process. Before SMED application, the average changeover time was 60.24 minutes, which was effectively brought down to 27.12 minutes—a 54.98% gain in efficiency. In addition, the layout of the workstations was improved to allow more effective operator movement, thus reducing time wasted on fetching or moving unrelated materials.

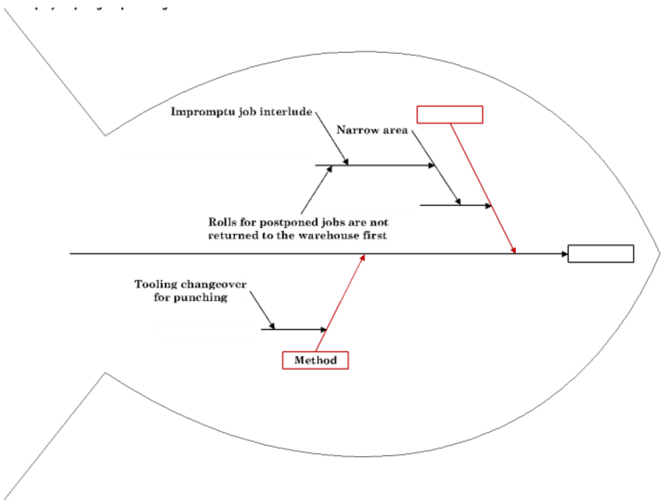


**Figure 3.** Fishbone for Motion Wastage

### *3.7. Excess Inventory Wastage Analysis*

Surplus inventory wastage, accounting for 13.29%, is brought about by some of the important causes like demand forecasting errors, delayed production, and extended storage of raw materials for over three years. Figure 4 gives the principal causes of surplus inventory. From the figure, most of these unused raw materials incurred quality deterioration—most notably yellowing of paper—through extended storage.

To counter this issue, a Just-In-Time (JIT) system has been implemented with the aim of reducing wastage related to inventories by maintaining the raw material in its optimum condition and minimizing unnecessary inventory. Further, materials that had passed their useful life were sold off as scrap and hence saved space for storage. This not only maximized the warehouse space but also generated additional revenue through the sale of obsolete materials [18].

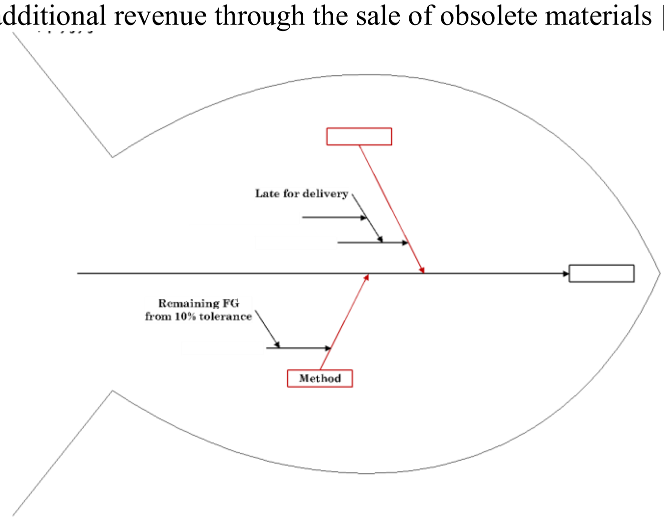


**Figure 4.** Fishbone for Inventory Wastage

### *3.8. Impact of Improvements on Customer Complaints*

One of the key indicators of success with Lean Manufacturing is the reduction in product defect-related customer complaints. Prior to the improvements, defect-related complaints were highest in June 2024. Following the implementation of an improved labeling system and targeted operator training, complaints about such matters gradually diminished as depicted in Figure 5. Problems related to ink blocking during printing were also mitigated following the interventions [15], [19]. Post-intervention data were gathered through structured interviews and brief questionnaires from 15 production operators and 2 shift leaders. Feedback identified improved clarity in the processing of raw materials through better labeling and witnessed a reduction in physical exhaustion from the alteration in the layout of the workplace. Operators also indicated that the SMED-based changeover procedure became easier to execute and less prone to errors, courtesy of standardized work procedure. These findings are consistent with earlier research identifying the role of employee commitment to helping maintain Lean Manufacturing practices over the long term. Before the improvements, the leading reason for defects was ink blockage, with complaint rates being highest during the period between June and December 2024. Subsequent to the deployment of early detection devices and routinized processes, complaints due to ink blockage significantly reduced, as can be seen in Figure 6's trend.

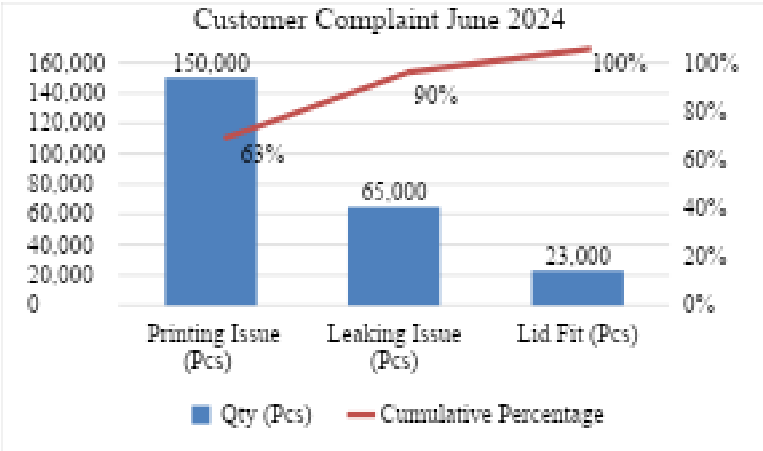


**Figure 5.** Quantity of Customer Complaint in June 2024

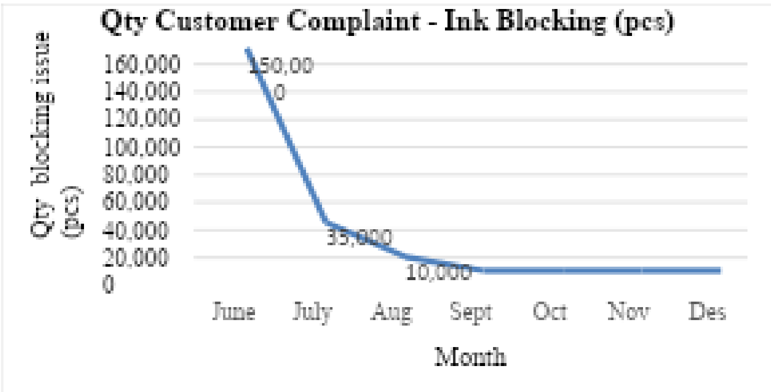


**Figure 6.** Quantity of Customer Complaint - Ink Blocking in June-Dec 2024

### *3.9. Efficiency Improvement through Lean Manufacturing*

The Lean Manufacturing practices had a beneficial effect on the company's operational efficiency. The reduction of time for non-value-added activity from 237.20 minutes to 204.07 minutes meant that the Process Cycle Efficiency (PCE) improved from 70.37% to 73.41%. The application of SMED not only reduced setup time but also improved overall manufacturing capacity.

This improvement also created financial advantages that were real, as the company was able to reduce defect manufacturing cost, enhance production efficiency, and optimize raw material utilization with the Just-In-Time (JIT) system. Specifically, financial advantages were realized through the reduction of product rejection losses—from around IDR 100,000,000 in June 2024 to IDR 42,000,000 until August 2024—equivalent to 58% reduction. Besides this, the higher production of 1,241 units per cycle enabled the company to produce greater volumes of orders without spending additional costs in terms of overtime. Also, selling old inventory under waste reduction program realized a net recovery of approximately IDR 15,000,000. These results are in alignment with previous research [20], which demonstrates that the implementation of Lean Manufacturing can drastically reduce waste and improve the performance of an operation. Further proof is from studies [21], which confirms that the implementation of Value Stream Mapping (VSM) and SMED for industrial use can reduce production lead times by 30% and increase overall capacity for output.

These improvements enable organizations to maintain higher levels of operating efficiency, generate competitiveness in manufacturing business, and avoid adverse effects of waste in manufacturing. As part of continued surveillance activities, a basic Statistical Process Control (SPC) chart was used to track the incidence rate of ink blocking on the press line—a top defect cause prior to intervention. The control chart indicated steady improvement in variability of defects, which remained within the lower control limits at the monitoring end of time. Also, downtime records accounted for a 14% decrease in machine idleness, much due to faster changeovers and improved material preparation at the workstation. Ongoing emphasis on Lean practices—varying from data-based processes to continuous training of operators—is expected to increasingly drive improved performance in the long term.

### *3.10. SMED Implementation to Reduce Setup Time*

In punching, the setup time for the tool changeover was 60.24 minutes prior to the introduction of SMED. This was reduced considerably with a change in bolt tightening from the use of an L-key to an impact wrench, as shown in Table 3. Table 3 presents a before-and-after comparison of setup times after SMED introduction.

**Table 3.** Setup Time Reduction after SMED Implementation

| Before SMED | After SMED | Difference |
|---|---|---|
| **60.24 minutes** | 27.12 minutes | -54.98% |

Adjustments to the tooling process, which saved 33.12 minutes from the setup time, yielded productivity growth of 1,241 units higher per production cycle.

### *3.11. Future State Mapping with Future Value Stream Mapping (Future VSM)*

Following the application of Lean Manufacturing principles, the Future State Value Stream Map (VSM) illustrates reduced time on non-value-added activity from 237.20 minutes to 204.07 minutes. Concurrently, the Process Cycle Efficiency (PCE) increased to 73.41%, as shown in Table 4, which illustrates before-and-after the intervention comparison of PCE values.

**Table 4.** Comparison of Process Cycle Efficiency (PCE) Before and After Improvement

| Method | PCE Before Improvement | PCE After Improvement |
|---|---|---|
| **Lean Manufacturing** | 70.37% | 73.41% |

As indicated in Figure 7, the Future State VSM shows the streamlined production flow following the application of Lean Manufacturing. Notable improvements are a 14% reduction in non-value-added time (from 237.20 to 204.07 minutes), optimized material flow, and elimination of process bottlenecks through SMED (achieved in 54.98% reduced changeover time) and JIT inventory management. The visual map reflects redesigned workstations, standardized procedures, and coordinated information flow—factors that all contribute to the achieved PCE improvement from 70.37% to 73.41%. This future-state design gives a strategic blueprint for sustaining long-term excellence in efficiency in the paper packaging manufacturing process. The new system is shown in the Future State Mapping in Figure 7.

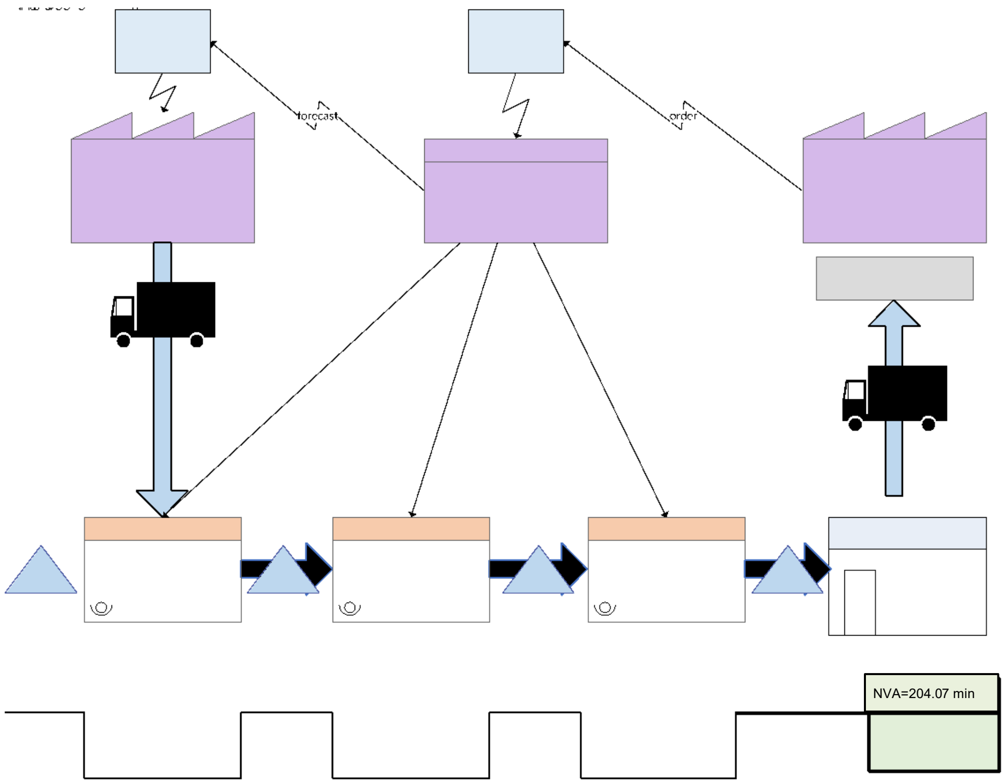

**Figure 7. Future State Value Stream Mapping**

*3.12. Impact of Lean Manufacturing Implementation*

This study confirms that implementation of Lean Manufacturing leads to a significant improvement in operation effectiveness based on Table 4. The most dramatic finding is a savings of setup time by 54.98% using the SMED technique. Secondly, non-value-added activity time decreased from 237.20 minutes to 204.07 minutes with an increase in Process Cycle Efficiency (PCE) from 70.37% to 73.41%. These findings are consistent with the past research work [20], which set that Lean Manufacturing reduces waste in production, maximizes efficiency in cycle time, and reduces the cost of operations by a substantial amount. These findings also complement the work of Pagliosa et al. [26], which set that an automatic implementation of Lean tools, including SMED and Just-In-Time (JIT), can attain the efficiency level of over 15% in small to medium-sized package manufacturing industries. Such coordination in different industrial environments highlights the scalability and transferability of the methodology employed in this research.

Lean Manufacturing imitation not only increases efficiency but also eliminates wastage along the manufacturing process [22]. Product defects can be minimized through better labeling systems and trained operators, thereby lessening error rates in manufacturing. Unnecessary motion is relieved through designing out the work environment and reducing tool change times; the literature on research indicates that such an intervention can enhance manufacturing productivity by up to 30%. Over-inventories are addressed through the application of JIT principles and sophisticated forecasting, both of which enable better inventory control. Past studies show that the implementation of JIT in supply chain management enhances production performance and reduces storage costs by up to 20%.

Lean Manufacturing also comes with a strong financial advantage to the firm. Reducing waste products lowers the cost of production, whereas streamlining the tooling changeover process maximizes production capacity so that the firm can be closer to customers in a more efficient manner. Moreover, the adoption of JIT system lowers the cost of raw material storage, enabling superior working capital utilization [25].

An earlier study [21] confirmed that the implementation of SMED and JIT to the food processing industry led to a reduction in costs of production by 15% and production by 11%. All this illustrates the ability of organizations to acquire more operational efficiency and increase their competitiveness in the industrial market.

The findings of this study add further evidence to the theoretical context of Lean Manufacturing with a focus on the scientific reduction of waste and refining process flow as core drivers of efficiency. The use of VSM and SMED are consonant with the tenets of the Toyota Production System in the reduction of muda (waste) and refinement of workflow. The outcome of the discovered efficiency of SMED to reduce the setup time is in agreement with that of Peña and Veliz (2024), who achieved a 52% improvement in a bakery production setting [6], and Gard and Purohit (2022), who achieved 15% reduction of costs in food processing industry through integrated SMED-JIT systems [21].

Besides, the 3.04% increase and 54.98% reduction in setup time observed in this research are in line with performance improvement made in other related industries. For instance, Alanya et al. (2024) cited a 4.5% increase in throughput efficiency following the implementation of VSM and layout redesign in the textile sector [5]. These standards across industries suggest that Lean tools such as VSM, SMED, and JIT offer scalable and adaptable performance improvement, if only industry-specific aspects—product nature, equipment arrangement, and labor capabilities—are appropriately controlled.

Theoretically, the systematic application of Waste Assessment Model (WAM) with concomitant diagnostic tools such as Fishbone Diagrams represents compliance with the Lean principle of addressing the causative factors rather than mere symptoms on the surface. This supports the necessity of the involvement of both quantitative measurements and qualitative analysis in the application of Lean solutions to intricate production systems.

## 4. Conclusion

The objective of this study is to identify production process inefficiencies of an Indonesian food packager company grounded on paper and recommend operational improvement strategies. Value Stream Mapping (VSM) and Waste Assessment Model (WAM) analysis identified the most frequent types of waste to be product defects (24.74%), motion waste (22.23%), and excess inventory (13.29%). These inefficiencies were addressed by the implementation of the Single-Minute Exchange of Dies (SMED) to reduce setup time, improved labeling of raw materials to reduce product defects, and the implementation of a Just-In-Time (JIT) system to simplify inventory management. As a result, Process Cycle Efficiency (PCE) increased from 70.37% to 73.41% and the manufacturing capacity went up by 1,241 units per production cycle.

The findings demonstrate the applicability of Lean Manufacturing for practical improvement of operational performance and waste reduction in the paper-based packaging industry. Additionally, the methodical application of WAM, supported by expert validation, facilitated a sound basis for prioritizing improvement initiatives.

Long-term, the Lean practices introduced—SMED and JIT particularly—offer standardizable methods that can be incrementally improved to achieve ongoing waste reduction. With respect to scalability, the tools and techniques utilized in this study find application in other packaging firms, e.g., plastic or metallic packaging, with appropriate consideration of industry-specific constraints.

In order to sustain improvement in performance in the long term, future monitoring must address key performance indicators such as defect rate, setup time, material yield, and overall equipment effectiveness (OEE). Such parameters enable organizations to track progress, identify deviations early, and establish a cycle of continuous improvement.

Future research must deal with Lean principle adaptation in a broader range of manufacturing sectors and evaluate the long-term impact of such interventions over extended time frames.

**Author Contributions**

The research effort was a joint endeavor. Yumeling led the foundational aspects, designing the study framework, acquiring and analyzing data, and drafting the initial manuscript. In parallel, Suharjito provided critical input by validating methodological choices and offering thorough editorial revisions that shaped the final narrative. Their combined efforts ensured a rigorous and coherent study. Both authors affirm the accuracy of the findings and approve the final submission.

**Data Availability**

The data supporting the findings of this study can be shared upon formal request. Interested parties should contact Yumeling, who will assess the request and provide access as appropriate.

**Declaration of AI and AI assisted technologies in the writing process**

The author(s) declare that no artificial intelligence (AI) or AI-assisted technologies were used in the preparation, writing, or editing of this manuscript. All aspects of the work were conducted and written solely by the author(s).

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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