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Integrating Lean Manufacturing and Environmental Sustainability: A Framework for the Automotive Component Industry

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Abstract: Environmental sustainability in the manufacturing industry has garnered widespread attention from researchers and practitioners. Many companies have adopted Lean Manufacturing (LM) principles to enhance their performance; however, they have often failed to reap the full benefits of implementing LM in terms of environmental sustainability. This study aims to build a framework combining LM and sustainability to improve environmental sustainability achievements and apply the framework in a company. The study employed a mixed-methods approach to gain an in-depth understanding of the integration of LM and sustainability in enhancing sustainable environmental performance. This study involved eight respondents in the Delphi, AHP, and FMEA processes (four managers and four supervisors). The findings indicate that the integration of LM and sustainability principles can improve environmental sustainability achievements, as demonstrated by the increase in the Environmental Sustainability Index (ESI = 92.8), which is measured based on three indicators of environmental sustainability: energy efficiency, material use, and water use. This study differs from previous works by operationalizing the PEMIC methodology as a practical framework for sustainable lean implementation in the automotive manufacturing sector. The findings of this study provide implications for the importance of environmental sustainability in achieving sustainable manufacturing performance.

Keywords: Lean manufacturing framework, environmental sustainability, Environmental Sustainability Index (ESI), PEMIC methodology, automotive manufacturing.

Introduction

The literature generally recognizes that the manufacturing industry plays a vital role in national development, driving economic growth and job creation while supporting the expansion of other sectors. The industrial sector also contributes to economic value creation and enhances national competitiveness [1][2]. Furthermore, existing studies emphasize that manufacturing companies must continuously improve their performance to remain competitive. Manufacturing performance refers to how efficiently and effectively a manufacturing company transforms raw materials into finished products [3][4].

Several experts have proposed various initiatives to support higher manufacturing performance, including the implementation of Lean Manufacturing (LM). Literature defines LM as an approach focused on minimizing waste throughout the product value stream to improve process efficiency, enhance customer trust, and produce better products and services [5]. Meanwhile, the concept of sustainability has also been emphasized as crucial within the manufacturing industry. In this context, sustainability refers to a company's ability to produce goods through economically viable processes that minimize negative environmental impacts while ensuring the safety and well-being of employees, communities, and users [6]. To achieve this, companies are encouraged to redesign their manufacturing systems through sustainable practices that enhance efficiency in energy, material, and water consumption. Sustainability achievements bring multiple benefits, including cost savings, improved workplace safety, and better regulatory compliance [7].

Of the three aspects of sustainability, this study focuses on environmental sustainability aspect, which refers to a company's ability to produce products and services in ways that minimize negative environmental impacts while ensuring that all production activities are safe for employees and the community [8]. The growing demand for environmental sustainability has led scholars to explore how traditional LM can be aligned with sustainability goals, giving rise to the concept of Sustainable Lean Manufacturing (SLM). SLM can be defined as the application of sustainability principles within manufacturing management to maintain and strengthen a company's competitive advantage, or as the interaction between LM and sustainability concepts to enhance sustainable manufacturing performance [9]. The application of SLM will produce numerous benefits, including ensuring quality and environmental compliance, reducing waste, and mitigating legal risks. Additionally, SLM can lead to increased production efficiency by utilizing less water, energy, and raw materials while also reducing environmental costs, enhancing occupational safety, and improving the company's image [1].

While LM has been widely cited as a generic approach to help companies become sustainable, Abualfaraa *et al.* [10] caution that LM implementation is a complex and multidimensional issue. Maware and Parsley [4] also report that successful LM implementation in one company does not guarantee similar results in other companies. In other words, the success of LM implementation remains inconsistent, with a relatively high failure rate. Key causes of LM failure include misunderstanding the implementation stages, misapplication of LM tools, and inadequate contextual understanding [5].

A literature review reveals that several experts have proposed various frameworks to integrate the concepts of LM and environmental sustainability. However, previous studies exhibit several limitations: focusing primarily on the impact of LM tools on environmental sustainability [11], examining only economic and operational performance [12], exploring LM–sustainability relationships through literature reviews [13], or proposing conceptual frameworks without demonstrating practical application [14].

To address these gaps, this study designs a framework for implementing LM to improve environmental sustainability in the automotive component industry and applies it through a case study. The automotive component industry serves as a critical link in the broader automotive value chain, where compliance with environmental sustainability is mandated under IATF 16949, an international quality management standard specific to this sector. This study also responds to Vasconcelos et al. [6], who highlight the need for further research to develop sustainability frameworks that explicitly consider environmental dimensions in the manufacturing industry.

Methods

Research Methods

The research employed a mixed-methods approach to gain an in-depth understanding of the application of LM in enhancing sustainable environmental performance in the manufacturing industry. The mixed-methods approach combines quantitative and qualitative elements to comprehensively address research questions [15]. A case study was conducted in an automotive component company located in DKI Jakarta Province, Indonesia. The company was selected based on its relevance to the IATF 16949 6th Edition, which will take effect on January 1, 2025. This international quality standard specifies requirements for the entire automotive industry supply chain, including component manufacturers. One of its internal audit scopes concerns environmental sustainability compliance, which requires companies to develop sustainable manufacturing practices and identify improvement areas.

Framework

This study proposes a five-stage framework for implementing LM to achieve environmental sustainability, which can be adopted by various manufacturing industries. As illustrated in Figure 1, the framework consists of five main stages referred to as PEMIC: Planning (P), Evaluation (E), Measurement (M), Improvement (I), and Control (C). These stages expand upon the PDCA cycle (Plan, Do, Check, Act), functioning as an iterative process to achieve continuous improvement toward environmental sustainability.

Specifically, the Planning stage (P) involves preparation activities such as obtaining research permits, forming teams, understanding business processes, and setting objectives. The Evaluation stage (E) includes assessing team adequacy and skills, identifying research areas, and conducting preliminary performance assessments. The Measurement stage (M) involves evaluating performance achievements using established indicators. The Improvement stage (I) focuses on refining processes or systems in areas that underperform, while the Control stage (C) ensures long-term maintenance of performance improvements.

Stage 1: SLM project planning

The first stage, SLM project planning, includes several activities: submitting research proposals to company leadership, forming a work team, determining objectives, mapping production processes, and identifying study areas. The tools used include interviews, document analysis, Pareto analysis, Gemba Walks, and SIPOC diagrams.

Stage	Input	Tools	Output
Planning	Project proposal Business process Waste Characteristics Process requirements Supporting documents	Interview, Expert judgment Pareto analysis Gemba Walk	Work team Waste list Management commitment Project theme
KPI Determination	Questionnaire Identified indicators	Delphi methods AHP	Valid and relevant indicators Indicator weight
Measurement	Questionnaire	Descriptive statistics Gemba Walk TLS Sus-VSM	Sus-VSM current condition MSI current condition
Repair	Sus-VSM current condition	FMEA Expert judgment	Proposed initiatives
Implementation and analysis	Proposed initiatives	Descriptive statistics Gemba Walk	Sus-VSM post repair MSI post repair
Control	Sus-VSM post improvement	Statistical process control	Work standardization

Monitoring and controlling

Figure 1. SLM implementation framework proposed in this study

Stage 2. Selection of environmental KPIs

The second stage involves selecting valid and relevant environmental sustainability KPIs within the company's context. The selected KPIs must be reliable, accurate, and accessible, measurable, assessable, and easy to implement. Table 1 presents indicators of environmental sustainability within the manufacturing industry.

Table 1. Environmental sustainability indicators in the context of the manufacturing industry

Indicators	**References**
Energy usage	[25] [26] [27]
Emission rate	[25] [26] [27]
Water usage	[12] [25][27]
Materials usage	[12] [25]
Amount of waste	[25]
Recycling rate	[25]
Scrap amount	[8] [25]
Use of renewable energy	[8] [26]

In determining the appropriate indicators, this study considered the views of an expert panel regarding indicator relevance. Following Mullender *et al.* [16], the Delphi method was employed to assess indicator suitability to the company's conditions. The Delphi method is an iterative approach aimed at achieving expert consensus through successive rounds of questionnaires. The process involved selecting experts, distributing the first questionnaire, analyzing feedback, and then issuing subsequent rounds until consensus was achieved.

Eight respondents participated in the Delphi process: four managers and four supervisors. All respondents held a bachelor's degree and had over ten years of experience. Based on their educational background, position, and tenure, they were considered competent to determine valid and relevant indicators for the company. Two parameters were used to assess indicator relevance: Weighted Average (WA) and Level of Consensus (LC). WA was calculated by multiplying each respondent's score by their assigned weight, then dividing by the total number of respondents. LC was determined by dividing the number of respondents in agreement by the total respondents. Indicators with $LC \geq 0.7$ and $WA \geq 4.0$ were selected as valid measures of environmental sustainability performance. Table 2 shows valid and relevant environmental sustainability Indicators in the context of company.

Companies mostly have limited resources; therefore, they need to prioritize indicators that will become the focus of their improvement efforts. For this reason, this study employs the Analytical Hierarchy Process (AHP) method to prioritize environmental sustainability indicators. Following the procedure outlined in Ainul Yaqin *et al.* [17], the weight of each indicator, as applied to the company, was obtained (Table 3).

Table 2. Relevance of environmental sustainability KPIs

Indicators	Relevance					WA	LC
	1	2	3	4	5		
Energy usage*	0	0	1	3	4	4.38	0.88
Emission	0	3	3	1	1	3.00	0.25
Water usage*	0	0	1	4	3	4.25	0.88
Use of raw materials	0	2	3	2	1	3.25	0.38
Amount of waste	2	3	2	0	1	2.38	0.13
Recycling rate	2	2	2	1	1	2.63	0.25
Scrap amount*	0	0	1	2	5	4.50	0.88
Use of renewable energy	1	3	2	2	0	2.63	0.25

As depicted in Table 3, the AHP analysis produced weighted values of 0.268 for the energy consumption indicator, 0.614 for material usage, and 0.117 for water usage, with a Consistency Ratio (CR) of 0.07. Because the CR value is below 0.10, it indicates an adequate consistency among respondents when comparing various indicators.

Table 3. Weight of environmental sustainability indicators

Indicators	Weight
Energy usage	0,268
Scrap amount	0,614
Waste amount	0,117
Consistency ratio (CR)	0,070

Stage 3. Measuring Environmental Sustainability Achievements

The third stage involves measuring environmental sustainability achievements. This stage aims to identify performance levels across all work areas, monitor progress toward targets, and support data-driven decision-making. Referring to Setiawan et al. [18], this study adopts the Traffic Light System (TLS) method to classify performance based on predefined thresholds: "green" for achievements that meet or exceed targets, "yellow" for achievements that are close to targets and require attention, or "red" for achievements that are below targets and therefore require immediate corrective action. Furthermore, this study uses Sustainable Value Stream Mapping (Sus-VSM) to visualize environmental sustainability achievements across each process area. Sus-VSM extends the traditional Value Stream Mapping (VSM) approach by integrating sustainability performance metrics [19].

Stage 4: Improvement of Environmental Sustainability Achievements

The next stage is the improvement stage, which applies to the Kaizen principle emphasizing continuous improvement for better performance [12]. Among various Lean Manufacturing (LM) tools, this study employs the Failure Mode and Effects Analysis (FMEA) method to identify and mitigate potential failures in the production process before they occur. The FMEA approach enables proactive risk assessment and the development of effective mitigation strategies, leading to enhanced process reliability and overall performance improvement [20].

Stage 5. Controlling Environmental Sustainability Achievements

The final stage involves process control. Among several control tools, this study selects the control chart method to monitor and improve processes by identifying variations and detecting early signs of problems. Control charts guide corrective actions to maintain process stability and consistency, ensuring continuous performance improvement and overall process excellence [21].

Results and Discussions

Preparation

This phase includes several preparatory activities: obtaining a research permit, forming a work team, defining objectives, and identifying the research area. The company is a manufacturing enterprise producing automotive components, specifically bolts. Based on document reviews, interviews with operators, assessments by two department heads, and a Pareto analysis, the bolt type X/01/OTO/04 production process was selected as the research focus.

The following considerations guided the selection. The Pareto analysis indicates that, among the four product types produced, this product accounts for the highest number and types of defects (79.2% of the total). Furthermore, material utilization efficiency for this product type is the lowest (E = 61.7%). Therefore, the study considers this product representative of the actual conditions and problems occurring on the production line. Figure 2 illustrates a SIPOC diagram of the company.

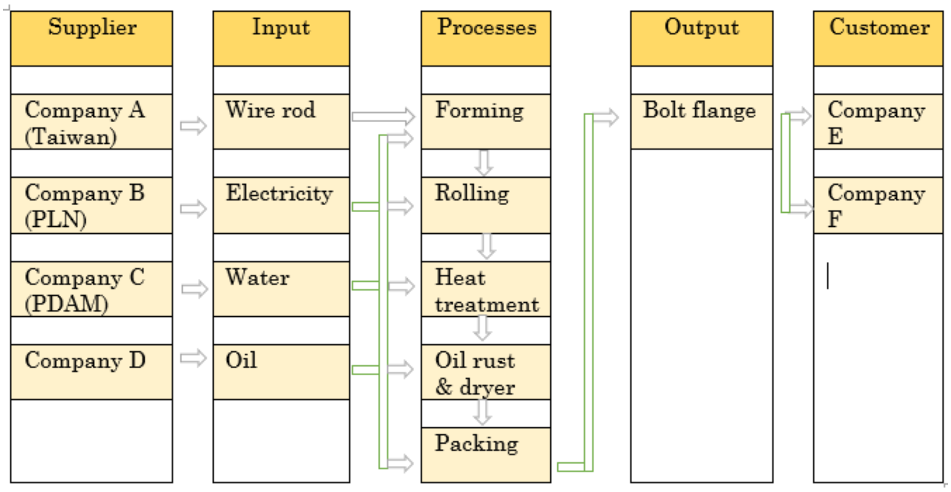


Figure 2. SIPOC diagram of the bolt production process

As shown in Figure 2, the bolt production process comprises the following steps: forming, rolling, heat treatment, oiling, and packaging. The forming process shapes the steel wire into the desired bolt profile (head and shank) by applying pressure through a mold without significant material removal. The rolling process forms threads by passing the steel wire through a series of dies that plastically deform the material. Heat treatment strengthens the bolt by altering its internal structure through heating and rapid cooling. The oil rust/dryer stage removes residual oil and dirt and dries the bolt. Finally, packaging involves packing bolts that pass quality inspection to meet customer requirements.

Relevant Indicators of Environmental Sustainability for Manufacturing Companies

A literature review identified numerous environmental sustainability indicators across contexts and industries. Referring to Rajabi et al. [22], the study considered several selection criteria: reliability and accessibility, measurability and ease of application, and stakeholder involvement. The review produced seven candidate environmental sustainability indicators for manufacturing (Table 1). Following Mullender *et al.* [16], a two-round Delphi process was conducted to determine which indicators were valid and relevant for the company. Indicators with $WA \geq 4.0$ and $LC \geq 0.70$ were considered valid for the company [24]. The Delphi results (Table 2) showed that three indicators failed to meet the thresholds, while five indicators passed. The three validated indicators were energy consumption, water consumption, and scrap amount. The AHP analysis subsequently ranked the validated indicators by relative weight: material usage ($\beta = 0.613$), energy usage ($\beta = 0.268$), and water usage ($\beta = 0.117$).

Measuring Environmental Sustainability

Environmental sustainability is a critical dimension of sustainable manufacturing performance. Measuring environmental sustainability is therefore essential to monitor achievements, support data-driven decision-making, minimize environmental impacts, conserve resources, and improve overall sustainability performance [38]. Such measures enable the company to identify areas for improvement, reduce waste, and operate more efficiently, leading ultimately to cost savings and a stronger competitive position. According to [37], environmental sustainability measurement is integral to the Kaizen process because it highlights both achievements and areas that require improvement or maintenance. Table 4 below presents a summary of environmental sustainability achievements.

Table 4. Achievement of environmental sustainability performance

Processes	Energy Usage	Water Usage	Scrap Amount
Forming	76.0	85.6	87.9
Rolling	75.4	85.4	89.0
Heat treatment	81.4	85.5	84.1
Oil rust and dryer	87.2	97.1	88.9
Packaging	86.3	94.5	91.5

As shown in Table 4, energy efficiency across the production line ranges from 75.4% (rolling) to 87.2% (oil rust & dryer). According to company standards, achievements below 80% are classified as red, achievements between 80% and 90% as yellow, and achievements above 90% as green. These performance categories are stipulated in the company Quality Manual, which sets standards across all business processes from raw material procurement through processing and delivery. For water efficiency, the lowest observed value is 85.4% (rolling) and the highest is 97.1% (oil rust & dryer). For material efficiency, the lowest occurs in the heat treatment process (84.1%) and the highest in packaging (91.5%). Material usage efficiency for a machine was calculated by dividing the amount of wasted material (scrap) by the established standard for scrap, multiplying by 100, and taking the average. For example, on one observation day the Heat Treatment machine produced 11 kg of scrap versus a standard of 70 kg, yielding 84.3% material efficiency. In the Packaging machine, scrap was 2 kg against a 20 kg standard, giving a material efficiency of 90.0%. Based on these measurements, the company prepared Environmentally Sustainable Value Stream Mapping (ES-VSM) for the current condition (Figure 3). ES-VSM is a tool that analyzes environmental performance in each work area from both lean and sustainability perspectives.

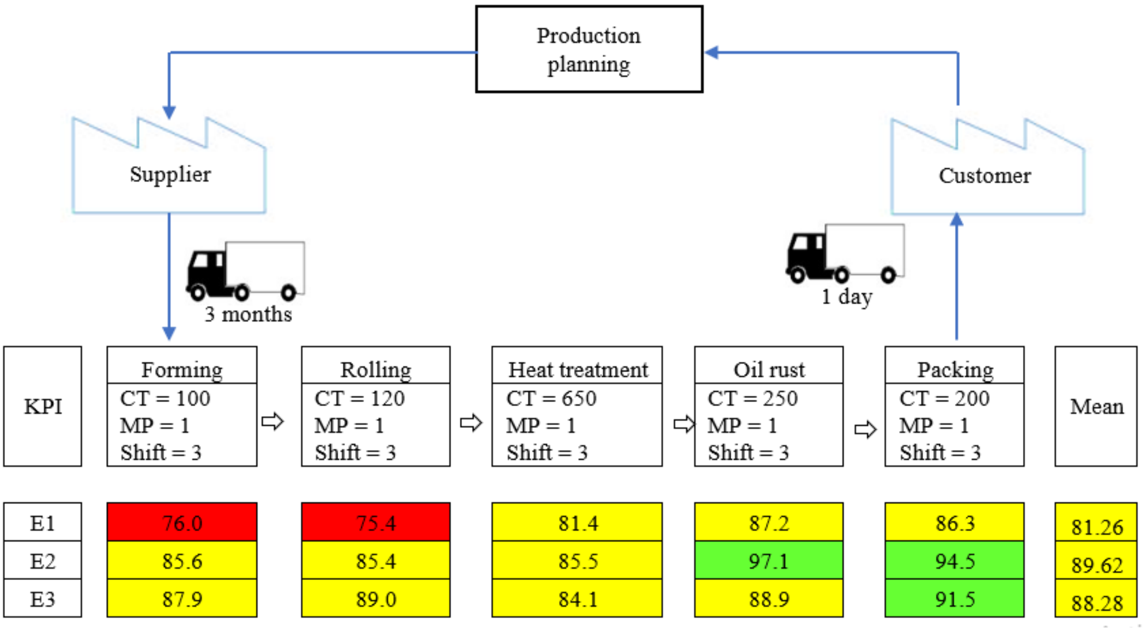


Figure 3. Current ES-VSM of the company

As shown in Figure 3, the analysis reveals that the energy efficiency (E1) in the Forming and Rolling processes is below 80.00%. Based on the company's established standards, achievements below 80% fall into the *red* category, those between 80% and 90% are classified as *yellow*, and those exceeding 90% are placed in the *green* category. In this study, the categorization of performance achievements also refers to the company's *Quality Manual* document, which defines performance standards for all business processes, from raw material procurement to processing and delivery. Therefore, the energy efficiency in these two processes is labeled "Red," while the energy efficiency in the Heat Treatment, Oil Rust and Dryer, and Packaging processes is labeled "Yellow."

For water efficiency (E2), the analysis shows that the Forming and Rolling processes fall into the "Yellow" category, whereas the Oil Rust and Dryer and Packaging processes fall into the "Green" category. Regarding the efficiency of material waste (E3), the analysis identifies that the Forming and Rolling processes fall into the "Yellow" category, while the Oil Rust and Dryer and Packaging processes fall into the "Green" category. Based on the environmental sustainability achievements of each work area, this study obtained an Environmental

Sustainability Index (ESI) of 82.59. The pre-improvement ESI score was calculated by multiplying the average achievement of each environmental sustainability indicator by its corresponding weight.

Improvements

The measurement results indicate that most of the company's environmental sustainability achievements fall within the *yellow* category. This finding serves as an early warning for the company to undertake immediate process improvements. In this context, the company should begin by addressing the indicators categorized as *red*—specifically, energy consumption. As shown in Figure 3, energy efficiency in the Forming and Rolling processes falls into the *red* category, suggesting that targeted improvement efforts are required to enhance energy performance in these areas. The improvement process is crucial as it reflects the Kaizen principle, which emphasizes continuous improvement to achieve superior conditions [12].

Among the various Lean Manufacturing (LM) tools discussed in the literature, this study employed Gemba Walk and Failure Mode and Effects Analysis (FMEA) to identify potential initiatives for improving environmental sustainability achievements. The Gemba Walk [24] was used to directly observe and understand energy efficiency in the Forming and Rolling work areas, while the FMEA [25] was applied to identify and mitigate potential failures that could affect energy efficiency before they occur. The selection of these tools was based on several considerations, including methodological simplicity, insights from employee interviews, team consensus, and assessments by departmental heads.

The FMEA team comprised nine members: four supervisors (Production, Engineering, Quality Assurance, and Business Development) and five machine operators (Forming, Rolling, Heat Treatment, Oil Rust and Dryer, and Packaging). All team members had worked at the company for more than ten years. Based on their experience, this study considers them sufficiently competent to identify and implement corrective actions to reduce potential failures in the production line.

Table 5 presents the recommended initiatives for improving energy efficiency at the company. As shown in the table, the FMEA team proposed six key actions aimed at enhancing energy performance, particularly for the Forming and Rolling machines. As previously noted, the performance metrics for both machines fall within the *red* category, underscoring the need for these improvement initiatives.

Table 5. Recommended actions to improve energy efficiency

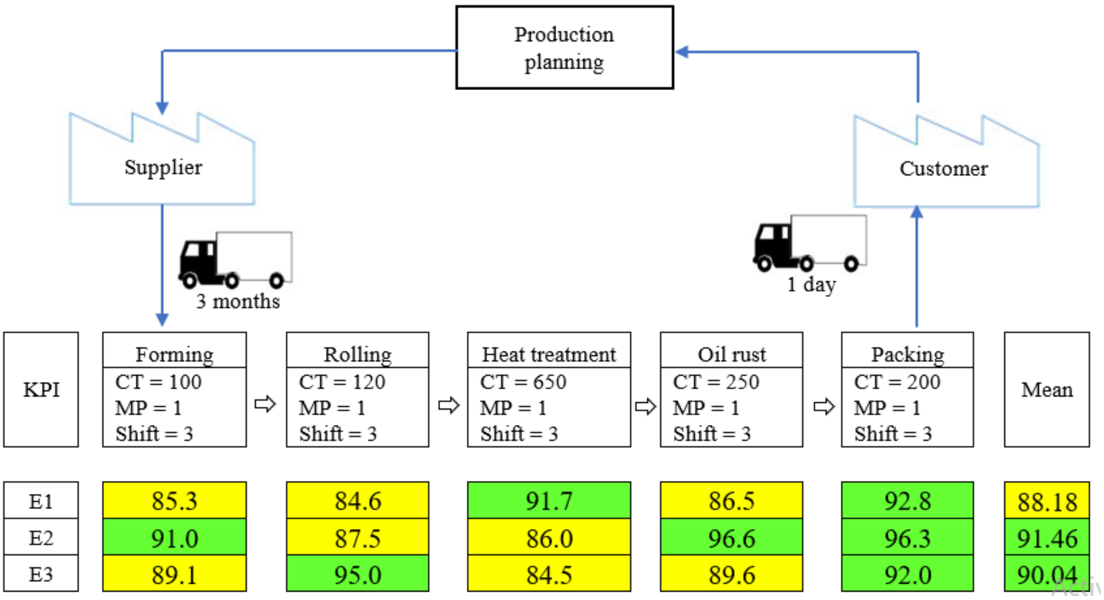
No.	Improvement Initiatives
1	Conduct relevant training for Forming and Rolling machine operators to reduce downtime, increase capacity, and decrease production losses.
2	Establish standard operating procedures and work instructions for Forming and Rolling processes.
3	Conduct an operator rolling system to improve operator flexibility and skills and increase workstation capacity.
4	Eliminate obstacles that cause machine speed reduction and slow cycle times.
5	Enhance workflows to boost production speed and minimize repetitive errors.
6	Implement a control system to ensure the availability of raw materials and components, ensuring smooth material flow, and mitigating disruptions that may affect machine capacity.

Following the implementation of these improvement initiatives, the company prepared an Environmentally Sustainable Value Stream Mapping (ES-VSM) for post-implementation conditions. This ES-VSM was used to evaluate the impact of the implemented improvements on the company's environmental sustainability achievements. Figure 4 illustrates the ES-VSM after implementation.

As previously discussed, this study applies the Sustainable Lean Manufacturing (SLM) approach as a means of achieving environmental sustainability within the company's production flow. SLM represents the interaction between lean manufacturing principles and sustainability concepts, realized through environmentally responsible practices across the production line. The company can achieve this by increasing efficiency in material use, water consumption, and energy utilization, reflecting its commitment to environmental responsibility and the preservation of natural resources.

As shown in Figure 4, the environmental performance of all production processes in the company has met the established requirements. For the energy efficiency indicator (E1), the Forming, Rolling, and Oil Rust and Dryer processes now fall into the *yellow* category, whereas the Heat Treatment and Packaging processes are classified as *green*. The average post-improvement energy efficiency is 88.1%. For the material efficiency indicator (E2), the Rolling and Heat Treatment processes are classified as *yellow*, while the Forming, Oil Rust and Dryer, and Packaging processes fall into the *green* category, with an average material efficiency of 91.4%. Figure 4 also shows that, after improvements, the average water efficiency (E3) in the production line reached 90.0%. In this case, the Forming, Heat Treatment, and Oil Rust and Dryer processes fall into the *yellow* category, while the Rolling and Packaging processes are classified as *green*.

Material efficiency serves as a key indicator of sustainable manufacturing performance, as it directly affects waste generation. Enhancing material efficiency reduces environmental impacts and contributes positively to sustainable manufacturing outcomes [26]. In line with Pauliuk and Heeren [27], this study views material efficiency as encompassing practices aimed at minimizing material consumption and waste while maximizing material value. Improving material efficiency yields multiple benefits for companies, including environmental impact reduction, cost savings, and enhanced overall sustainability.



KPI	Forming	Rolling	Heat treatment	Oil rust	Packing	Mean
E1	85.3	84.6	91.7	86.5	92.8	88.18
E2	91.0	87.5	86.0	96.6	96.3	91.46
E3	89.1	95.0	84.5	89.6	92.0	90.04

Figure 4. Future ES-VSM of the company

Literature has proposed several approaches to measuring material usage efficiency. Referring to Ongbali *et al.* [28], this study assessed material usage efficiency based on the amount of scrap generated in each work area of the production line. The measurement results indicate that performance in all work areas falls within either the *Yellow* or *Green* category. This finding indirectly supports the notion that the Lean Manufacturing (LM) implementation framework proposed in this study can facilitate the achievement of environmental sustainability. Nevertheless, this study recommends that the company continues to control its performance by selecting and utilizing appropriate LM tools, providing employee training, and maintaining continuous management support.

The third indicator of environmental performance examined in this study is water use efficiency. This KPI refers to the effectiveness of water utilization in producing goods, minimizing waste, and maximizing resource use. Water use efficiency is an important component of environmental sustainability, as it serves as a key indicator of sustainable manufacturing performance, contributing to cost reduction, environmental protection, and regulatory compliance [29]. As shown in Figure 4, the efficiency of water use across all work areas falls within the *Yellow* and *Green* categories. This achievement demonstrates that water consumption in the production line remains below the maximum standard established by the company. Based on the environmental sustainability achievements of each work area, the analysis yielded an Environmental Sustainability Index (ESI) of 92.38. The post-improvement ESI score was calculated by multiplying the average achievement of each environmental sustainability indicator by its corresponding weight.

These findings support the concept of Abdul Ghafar and Razali [30], who stated that, in addition to improving operational performance, Sustainable Lean Manufacturing (SLM) practices can also have a positive impact on environmental sustainability in the manufacturing sector. This study empirically confirms that SLM implementation can improve the Environmental Sustainability Index within the automotive components industry. Moreover, the findings are consistent with the research of Abdul Shukor and Ng [31], who identified material usage, energy usage, and water usage as valid indicators for assessing environmental sustainability. This study extends their work by providing prioritized weights for each environmental sustainability indicator. As a manufacturing company, the case study firm requires various resources, including water. In the production process, water is used as both a cooling medium and for cleaning operations. However, manufacturing companies must acknowledge that water use has a significant environmental impact. Therefore, it is crucial for companies to understand the implications of water consumption in order to effectively address environmental challenges [32]. In this regard, the study emphasizes that companies must take proactive measures to mitigate the negative impacts of water use within their processes to achieve environmental sustainability.

Accordingly, interdisciplinary and green manufacturing concepts should be implemented comprehensively to achieve a balance between environmental, industrial, and social objectives [33, 34]. Companies can achieve this by adopting several initiatives, including the 5R concept (Reduce, Reuse, Recycle, Recover, and Redesign), conducting leak detection and repair, improving process optimization, implementing productive maintenance, and providing targeted training for employees.

The selection of tools and methods can be tailored to the company's data variance, sampling frequency, and process complexity. Furthermore, firms that have adopted Industry 4.0 infrastructure, including sensors, cyber-physical systems, and cloud platforms—can extend the *Measuring* and *Improving* phases to a higher level of automation. Real-time environmental and energy data captured via IoT sensors can be integrated into adaptive control loops or predictive models [35]. These systems enable dynamic adjustments to process parameters in response to deviations in water, energy, or material usage, thereby transforming the PEMIC framework into a proactive, data-driven model.

In contexts where rich, continuous data are available, the *Control* stage may evolve beyond traditional static control charts to incorporate adaptive Statistical Process Control (SPC) or digital twin–based monitoring. For example, digital twin models informed by IoT data can simulate process behavior and recommend sustainable interventions *in silico* prior to implementation [36]. This hierarchical flexibility ensures that the PEMIC framework remains scalable—ranging from manual, chart-based control in low-data environments to real-time, model-informed optimization in advanced manufacturing settings.

Conclusions

This study proposes a comprehensive framework for implementing Sustainable Lean Manufacturing (SLM) to achieve environmental sustainability. The framework comprises five main stages: (1) SLM project planning, (2) establishing and weighting environmental sustainability indicators, (3) measuring environmental sustainability achievements, (4) improving processes based on SLM and sustainability principles, and (5) controlling outcomes to maintain sustainable performance.

The implementation of the proposed framework demonstrated a positive impact on enhancing environmental sustainability in the automotive components industry. The results revealed a measurable increase in environmental sustainability scores for each process in the production line, and notably, no work areas remained within the *red* (high-risk) category. Overall, the Environmental Sustainability Index (ESI) increased to 92.38%, placing the company within the *green* (low risk) category.

The findings have two implications. First, automotive component manufacturers must recognize that implementing SLM to achieve environmental sustainability is a complex and multifaceted issue. Considering the limited availability of resources, companies need to identify critical work areas that require immediate improvement. Therefore, companies need to prioritize improvements based on environmental sustainability achievements in each work area. The company can carry out by mapping the risk priority number (RPN) of each indicator across all work areas. Companies can operationalize this by mapping the Risk Priority Number (RPN) of each indicator and focusing improvement efforts on areas with high RPN scores that fall into the red (high-risk) category.

Second, to achieve environmental sustainability, companies must enhance the energy efficiency of their production machines. This can be accomplished through several measures, including installing variable frequency drives, using high-efficiency motors and bearings, integrating sensors and controllers, and implementing intelligent maintenance and production scheduling.

Although the research results demonstrate that the proposed framework positively influences environmental sustainability outcomes, two limitations should be acknowledged. First, the case study's application of the framework was confined to a single company. To generalize the findings, future research should apply the framework to a broader range of firms within similar industrial contexts. Second, the respondents participating in the Delphi, AHP, and FMEA processes were drawn exclusively from within the company. To gain a more comprehensive understanding of environmental sustainability in manufacturing, future studies should involve a wider spectrum of stakeholders—such as government representatives, suppliers, customers, local communities, and non-governmental organizations.

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References

[1] F. E. Touriki, I. Benkhati, S. S. Kamble, A. Belhadi, and S. E. Fezazi, "An integrated smart, green, resilient, and lean manufacturing framework: A literature review and future research directions," *Journal of Cleaner Production*, vol. 319, no. 1, pp. 1–18, 2021. doi: https://doi.org/10.1016/j.jclepro.2021.128691.

[2] A. K. Digalwar, S. Dambhare, and S. Saraswat, "Social sustainability assessment framework for Indian manufacturing industry," *Materials Today*: *Proceedings*, vol. 28, no. 2, pp. 591–598, 2020. doi: https://doi.org/10.1016/j.matpr.2019.12.226.

[3] I. Leksic, N. Stefanic, and I. Veza, "The impact of using different lean manufacturing tools on waste reduction," *Advances in Production Engineering & Management*, vol. 15, no. 1, pp. 81–92, 2020. doi: https://doi.org/10.14743/apem2020.1.351.

[4] C. Maware and D. M. Parsley, "The Challenges of Lean Transformation and Implementation in the Manufacturing Sector," *Sustainability*, vol. 14, no. 10, pp. 1–24, 2022. doi: https://doi.org/10.3390/su14106287.

[5] A. J. Naeemah and K. Y. Wong, "Selection methods of lean management tools: A review," *International Journal of Productivity and Performance Management*, vol. 72, no. 4, pp. 1077–1110, 2023. doi: https://doi.org/10.1108/IJPPM-04-2021-0198.

[6] A. F. Vasconcelos, I. A. R. González, M. A. Fernández, A. Z. Santiago, and G. R. Romage, "Applying a Delphi method to assess the sustainability in SMEs: An approach of triple bottom line," *Revista de Gestão Social e Ambiental*, vol. 18, no. 11, e09690, 2024. doi: https://doi.org/10.24857/rgsa.v18n11-215.

[7] M. Q. Murad, W. F. Sales, and V. A. Feraressi, "Metric-based approach to assess sustainable manufacturing performance at manufacturing process levels," *International Journal of Sustainable Engineering*, vol. 14, no. 6, pp. 1342–1352, 2021. doi: https://doi.org/10.1080/19397038.2021.1978588.

[8] T. Sakao, N. Bocken, and N. Nasr, "Implementing circular economy activities in manufacturing for environmental sustainability," *CIRP Annals – Manufacturing Technology*, vol. 73, pp. 457–481, 2024. doi: https://doi.org/10.1016/j.cirp.2024.06.002.

[9] C. Ciliberto, K. Szopik-Depczynska, and M. Tarczynska-Luniewska, "Enabling the circular economy transition: A sustainable lean manufacturing recipe for Industry 4.0," *Business Strategy and the Environment*, vol. 30, no. 1, pp. 3255–3272, 2021. doi: https://doi.org/10.1002/bse.2801.

[10] W. Abualfaraa, K. Salonitis, A. Al-Ashaab, and M. Ala'raj, "Lean-green manufacturing practices and their link with sustainability: A critical review," *Sustainability*, vol. 12, no. 3, pp. 1–21, 2020. doi: https://doi.org/10.3390/su12030981.

[11] A. A. Ghafar and M. N. Razali, "The significant of lean practice on the sustainability performance in automotive manufacturing industry," *Journal of Modern Manufacturing Systems and Technology*, vol. 6, no. 2, pp. 83–89, 2022. doi: https://doi.org/10.15282/jmmst.v6i2.8562.

[12] J. R. Diaz-Reza, J. L. Garcia-Alcaraz, A. J. Gil-Lopez, and A. Realyvasquez-Vargas, "Lean manufacturing tools as drivers of social sustainability in the Mexican maquiladora industry," *Computers and Industrial Engineering*, vol. 196, 2024. doi: https://doi.org/10.1016/j.cie.2024.110516.

[13] L. M. Kaban, "Unveiling the sustainability of lean production," *Asian Journal of Economics, Business and Accounting*, vol. 23, no. 22, pp. 435–440, 2023. doi: https://doi.org/10.9734/ajeba/2023/v23i221163.

[14] M. A. Abobakr, M. G. Abdel-Kader, and A. F. Elbayoumi, "The impact of lean manufacturing practices on sustainability performance: A natural resource-based view," *Journal of Modern Accounting and Auditing*, vol. 18, no. 3, pp. 115–130, 2022. doi: https://doi.org/10.17265/1548-6583/2022.03.002.

[15] L. R. Sharma, S. Bidari, and R. Sapkota, "Exploring the mixed methods research design: types, purposes, strengths, challenges, and criticisms," *Global Academic Journal of Linguistics and Literature*, vol. 5, no. 1, pp. 3–12, 2023. doi: https://doi.org/10.36348/gajll.2023.v05i01.002.

[16] S. M. Mullender, M. Sandor, and A. Pisanelli, "A delphi-style approach for developing an integrated food/non-food system sustainability assessment tool," *Environmental Impact Assessment Review*, vol. 84, 2020. doi: https://doi.org/10.1016/j.eiar.2020.106415.

[17] A. M. Ainul Yaqin, M. J. Rosyid, V. A. Leksono, and A. D. Wantira, "a preference-oriented multi-criteria decision model for stunting prevention food basket ranking using ahp-topsis," *Jurnal Teknik Industri: Jurnal Keilmuan dan Aplikasi Teknik Industri*, vol. 26, no. 2, pp. 145–156, 2024. doi: https://doi.org/10.9744/jti.26.2.145-156.

[18] A. R. Setiawan, E. Gravitiani, and M. Rahardjo, "Production cost efficiency analysis of regional water companies in eastern Indonesia," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, Apr. 2021. doi: https://doi.org/10.1088/1755-1315/724/1/012012.

[19] W. Faulkner and F. Badurdeen, "Sustainable value stream mapping (Sus-VSM): Methodology to visualize and assess manufacturing sustainability performance," *Journal of Cleaner Production*, vol. 85, pp. 8–18, 2014. doi: https://doi.org/10.1016/j.jclepro.2014.05.042.

[20] A. T. Panudju, H. Sitorus, U. Marfuah, W. Sudarwati, and N. Nurhasanah, "Risk mitigation of air knocker using fuzzy fmea-aHP: A case study," *Jurnal Teknik Industri: Jurnal Keilmuan dan Aplikasi Teknik Industri*, vol. 26, no. 2, pp. 193–206, 2024. doi: https://doi.org/10.9744/jti.26.2.193-206.

[21] Z. J. Viharos and R. Jakab, "Reinforcement learning for statistical process control in manufacturing," *Measurement*, vol. 182, 2021. doi: https://doi.org/10.1016/j.measurement.2021.109616.

[22] S. Rajabi, S. El-Sayegh, and L. Romdhane, "Identification and assessment of sustainability performance indicators for construction projects," *Environmental and Sustainability Indicators*, vol. 15, 2022. doi: https://doi.org/10.1016/j.indic.2022.100193.

[23] X. Brioso and F. Cruzado-Ramos, "Model of evaluation of sustainability performance in building projects integrating lean, through the Delphi method," in *IGLC 28 – 28th Annual Conference of the International Group for Lean Constructio*n, pp. 781–792, 2020. doi: https://doi.org/10.24928/2020/0039.

[24] M. Ferrazzi, S. Frecassetti, and A. Bilancia, "Investigating the influence of lean manufacturing approach on environmental performance: A systematic literature review," *The International Journal of Advanced Manufacturing Technology*, vol. 136, pp. 4025–4044, 2025. doi: https://doi.org/10.1007/s00170-024-13215-5.

[25] B. Salah, M. Alnahhal, and M. Ali, "Risk prioritization using a modified FMEA analysis in industry 4.0," *Journal of Engineering Research*, vol. 11, no. 4, pp. 460–468, 2023. doi: https://doi.org/10.1016/j.jer.2023.07.001.

[26] V. Swarnakar, A. R. Singh, and A. K. Tiwari, "Evaluation of key performance indicators for sustainability assessment in automotive component manufacturing organization," *Materials Today: Proceedings*, vol. 47, pp. 5755–5759, 2021. doi: https://doi.org/10.1016/j.matpr.2021.04.045.

[27] S. Pauliuk and N. Heeren, "Material efficiency and its contribution to climate change mitigation in Germany: A deep decarbonization scenario analysis until 2060," *Journal of Industrial Ecology*, vol. 25, no. 2, pp. 479–493, 2021. doi: https://doi.org/10.1111/jiec.13091.

[28] S. O. Ongbali, S. Oladipupo, S. A. Afolalu, M. O. Udo, and R. O. Leramo, "Material efficiency: A key sustainable manufacturing strategy," in *IOP Conference Series: Materials Science and Engineering*, vol. 1036, 2021. doi: https://doi.org/10.1088/1757-899X/1036/1/012078.

[29] R. Chourasiya, S. Pandey, and R. K. Malviya, "Towards sustainable success: A framework for assessing performance of sustainable manufacturing adoption in textile industry," *Sustainable Futures*, vol. 7, 100216, 2024. doi: https://doi.org/10.1016/j.sftr.2024.100216.

[30] A. A. Abdul Ghafar and N. Mohd Razali, "The significant of lean practice on the sustainability performance in automotive manufacturing industry," *Journal of Modern Manufacturing Systems and Technology*, vol. 6, no. 2, pp. 83–89, 2022. doi: https://doi.org/10.15282/jmmst.v6i2.8562.

[31] S. Abdul Shukor and G. K. Ng, "Environmental indicators for sustainability assessment in edible oil processing industry based on delphi method," *Cleaner Engineering and Technology*, vol. 10, 2022. doi: https://doi.org/10.1016/j.clet.2022.100558.

[32] T. Amtulbari, J. Rimsha, M. Adeel, and Y. Abdullah, "Equitable water uses and environmental sustainability," *Current directions in water scarcity research* 135–148, 2024. doi: https://doi.org/10.1016/b978-0-443-23631-0.00009-1.

[33] U. S. Purwanto, A. S. Sujiwo, and M. Susanti, "Analysis of supporting factors of the successful implementation of green manufacturing for Indonesian Manufacturing SMEs," *AMCA Journal of Science and Technology*, vol. 3, no. 1, pp. 13–19, 2023. doi: https://doi.org/10.51773/ajst.v3i1.199.

[34] R. von Hellfeld et al., "The need for interdisciplinary research in marine sciences – A MERry outlook," *Frontiers in Marine Science*, vol. 11, 1392394, 2024. doi: https://doi.org/10.3389/fmars.2024.1392394.

[35] M. A. M. Nitol Saha, M. Rahman, M. S. A. Alam Khan, and M. Shafiul Alam Khan, "IoT-*Driven Cloud-based Energy and Environment Monitoring System for Manufacturing Industry,*" arXiv, 2024. Available: https://arxiv.org/abs/2404.11771.

[36] A. Fuller, Z. Fan, C. Day, and C. Barlow, "Digital twin: Enabling technologies, challenges and open research," arXiv, 2019. Available: https://arxiv.org/abs/1911.01276.

[37] M. K. Denu, Y. Bentley, and Y. Duan, "Social sustainability performance: Developing and validating measures in the context of emerging African economies," *Journal of Cleaner Production*, vol. 412, 137391, 2023. doi: https://doi.org/10.1016/j.jclepro.2023.137391.

[38] N. Kumar and K. Mathiyazhagan, "Sustainability in lean manufacturing: a systematic literature review," *International Journal of Business Excellence*, vol. 20, no. 3, pp. 295–321, 2020. doi: https://doi.org/10.1504/IJBEX.2019.10024618.