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A Hybrid BWM–Sustainable VSM Framework for Assessing Manufacturing Sustainability: Evidence from Indonesia's Coffee Industry

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ABSTRACT

Sustainability in the manufacturing industry is a strategic issue that encompasses economic, environmental, and social aspects. However, there is still a limited number of comprehensive and consistent evaluation approaches to assess sustainability performance quantitatively and in an integrated manner. This study aims to develop a new evaluation framework that combines the Delphi method, Best-Worst Method (BWM), and Sustainable Value Stream Mapping (Sus-VSM), supported by Traffic Light System (TLS) visualisation, to assess manufacturing sustainability performance holistically. The Delphi method is employed to identify relevant sustainability indicators in accordance with the Triple Bottom Line principle. At the same time, BWM is applied to determine the priority weight of each indicator. Furthermore, indicator efficiency is measured using a specific formula and visualised in a Sus-VSM process map equipped with a TLS colour system. A case study was conducted on the coffee processing industry in Indonesia. The results indicate that time and inventory indicators exhibit low efficiency levels, particularly during the stages of raw material reception, washing, packaging, and storage. On the other hand, quality and cost criteria contributed most to overall weight globally, consistent with the company management priority on economy. The score of the Manufacturing Sustainability Index (MSI) was 80.95% indicating a reasonable performance level in sustainability, but with considerable potential for further improvement, especially on social and environmental issues. The resultant framework was demonstrated to be helpful in charting total sustainable performance, and it can ultimately be utilised as a strategic decision support system. Theoretically, this study contributes to the development of manufacturing sustainability evaluation methods. In practice, this framework can be implemented to improve process efficiency and operational sustainability in the agro-industry sector.

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1. Introduction

In recent decades, the manufacturing industry has tended to focus on achieving economic efficiency. However, this approach often ignores negative impacts on the environment and social aspects [1]. Nowadays, awareness of the importance of sustainability in the production process is increasing [2, 3]. Companies are no longer only required to generate profits, but also to be responsible for the environment and social welfare [4, 5]. The concept of sustainable manufacturing comes as a solution to these challenges. This concept emphasises the need for production processes that are efficient, environmentally friendly, and socially just [6]. Sustainability efforts include reducing material and energy consumption, good waste management, and protecting occupational health and safety [7]. To support this, many companies adopt the Triple Bottom Line (TBL) approach. This approach assesses sustainability performance from three main dimensions: economic, social, and environmental [8]. Assessing sustainable manufacturing performance is a crucial step in identifying inefficient processes [9]. Additionally, this assessment ensures that production activities align with long-term sustainability principles. As the need for a comprehensive evaluation system increases, various approaches are being developed. The aim is to provide an assessment framework that is measurable, integrative and relevant to the sustainability challenges in the manufacturing sector.

In assessing manufacturing sustainability, numerous studies have employed various indicators from economic, social, and environmental perspectives [10, 11]. However, there are still some limitations in the approach used. One of them is that not many studies have applied the Best Worst Method (BWM) in the weighting process of sustainability indicators. In fact, BWM is more efficient and easier to use than the Analytic Hierarchy Process (AHP), because it only requires a few pairwise comparisons [12, 13]. Additionally, BWM is more consistent and does not produce repetitive data, resulting in more reliable results [14, 15]. Some previous studies, such as those conducted by Huang and Badurdeen [16], Soltani, et al. [17], Mubin, et al. [5] and Dewi, et al. [18], still use AHP as a weighting method. Although commonly used, AHP has limitations, particularly when the number of indicators being assessed is quite large. In addition, most studies have not combined weighting, efficiency measurement, and outcome mapping in a single evaluation framework. The assessment is still done partially and does not consider the relationship between weights and actual performance [19]. In response to these gaps, the present study introduces an integrated evaluation framework that combines the Delphi method, Best-Worst Method (BWM), and Sustainable Value Stream Mapping (Sus-VSM), enhanced with a Traffic Light System (TLS) visualisation, to enable a more holistic and actionable assessment of manufacturing sustainability.

Based on the discussion in the previous section, most prior studies have not employed efficient and consistent weighting methods for evaluating manufacturing sustainability performance. These studies have predominantly focused on specific sectors such as electronics [20], manufacturing [21], beverage [22], and plastics [5]. Consequently, there is a limited understanding of sustainability performance in other critical sectors, particularly the agro-industry. This study makes a significant contribution by applying a sustainability assessment framework to the coffee processing industry. This sector has received limited scholarly attention. Notably, this industry exhibits distinctive characteristics, including a staged production process, substantial energy consumption, potential for generating organic waste, and considerable variability in workload across production stages [23, 24]. Therefore, a comprehensive and context-appropriate evaluation approach is essential. To address this gap, the present study proposes an integrated

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framework for evaluating sustainable manufacturing performance, combining the Delphi method, Best-Worst Method (BWM), Sustainable Value Stream Mapping (Sus-VSM), and the Traffic Light System (TLS). The Delphi method is employed to identify relevant sustainability indicators. At the same time, BWM is used to determine the weights of both indicators and production stages. Indicator efficiency is then analysed and visualized using TLS within the Sus-VSM framework. The final output of the evaluation is the Manufacturing Sustainability Index (MSI), which quantitatively and comprehensively represents the sustainability level of the manufacturing process.

This study makes a significant contribution to the advancement of knowledge, particularly in the field of sustainable manufacturing performance assessment. The primary contribution lies in the development of a novel evaluation framework that integrates the Delphi method, Best-Worst Method (BWM), Sustainable Value Stream Mapping (Sus-VSM), and the Traffic Light System (TLS). This integrated framework is designed to provide a more comprehensive and systematic evaluation of sustainability performance across production lines. The second significant contribution of this research is the application of the proposed framework to the coffee processing industry. Through this application, the study effectively captures and visualises the sustainability performance at each stage of the production process in a quantitative manner. By utilising this framework, decision-makers in the coffee processing industry can conduct more targeted performance evaluations, identify specific indicators that require improvement, and pinpoint production stages that demand greater attention to achieve optimal sustainable manufacturing.

2. Methods

2.1 Proposed Framework for Evaluating Manufacturing Sustainability

This section presents the proposed framework for evaluating sustainable manufacturing performance. Figure 1 illustrates the sustainability assessment framework developed in this study. The framework comprises two main stages: (1) the evaluation of indicator relevance and (2) the assessment of sustainable manufacturing performance based on the Triple Bottom Line (TBL) perspective. The primary objective of this framework is to assess and enhance manufacturing performance by minimising waste, reducing environmental impact, and improving overall operational efficiency [25, 26]. The first stage begins with the selection of relevant indicators, which are derived from lean manufacturing principles aligned with the TBL dimensions, economic, social, and environmental [27]. The incorporation of lean-based indicators is essential for strengthening process efficiency and supporting the achievement of sustainability goals [28]. Lean manufacturing is not only a tool for improving efficiency, but also a strategic approach to conserving resources and sustainably optimising production processes [29]. By utilising these indicators, companies can systematically evaluate their performance against sustainability targets and identify critical areas that require improvement.

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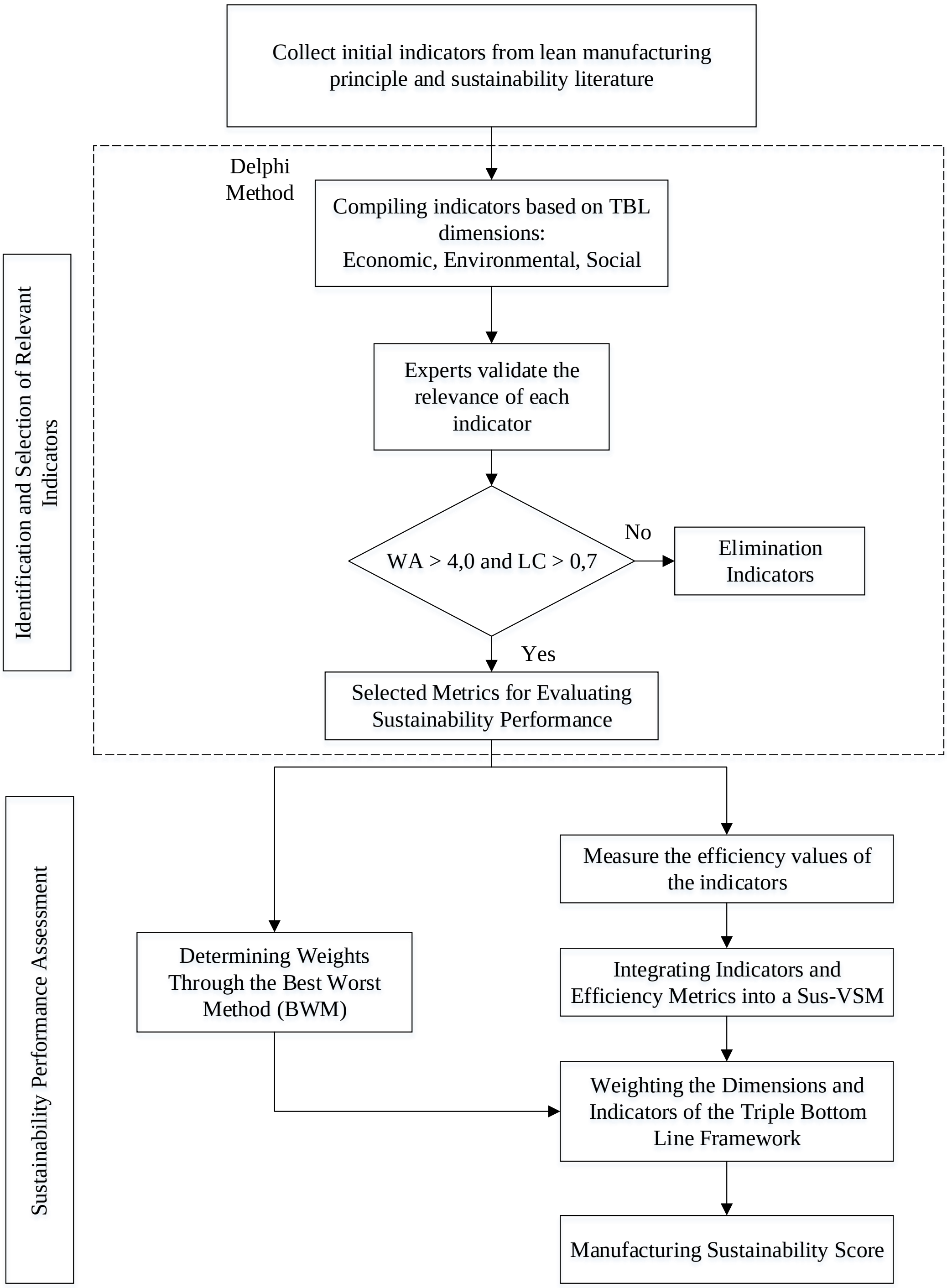

Figure 1. Proposed framework for assessing sustainability in manufacturing

To determine the relevant indicators for assessing sustainable manufacturing performance, a validation process was conducted using the Delphi method. This method is a consensus-based decision-making technique that systematically gathers the judgments of a panel of experts through iterative rounds [30]. The primary objective of this process is to reach agreement on the most representative indicators tailored to the specific industrial context under investigation. The assessment was carried out using a quantitative approach based on the Weighted Average (WA) and Level of Consensus (LC), ensuring that the selected indicators are truly significant in supporting corporate sustainability goals [31]. According to the study by Hartini, et al. [22], an indicator is considered relevant if it achieves a WA score of ≥ 4.0 and an LC score of ≥ 0.7. The formulas for calculating WA and LC are presented in Equations (1) and (2), where SR_i represents the relevance score assigned by the i-th respondent, FNR denotes the number of respondents who rated the indicator as relevant, and Nr is the total number of respondents. The indicator relevance assessment employed a 5-point Likert scale, where a score of 1 indicates "very irrelevant" and a score of 5 indicates "very highly relevant."

$$WA = \frac{\sum SR_i}{Nr} \quad (1)$$

$$LC = \frac{FNR}{Nr} \quad (2)$$

Subsequently, efficiency scores were calculated for each selected sustainability indicator, and the results were mapped using the Sustainable Value Stream Mapping (Sus-VSM) approach to support the Manufacturing Sustainability Assessment (MSA) process. The efficiency values were derived from specific formulas assigned to each indicator, as detailed in Table 1, encompassing the economic, environmental, and social dimensions. This step aims to identify performance achievement levels across the indicators and highlight areas requiring improvement. Following this, the indicators were prioritised using the Best-Worst Method (BWM). This approach was employed to rank the indicators based on their relative importance, thereby facilitating a more objective evaluation of sustainable manufacturing performance [32]. BWM is a multi-criteria decision-making (MCDM) technique that utilises two comparison vectors: one comparing the best indicator to all others, and the other comparing all indicators to the worst one [33]. In practice, this method applies a scoring scale ranging from 1 to 9, where a score of 1 denotes equal importance and a score of 9 indicates that one indicator is significantly more important than another [11, 34]. The weighting assessment in this study was conducted through Focus Group Discussions (FGDs) with domain experts to establish a consensus on the priority level of each indicator within the context of sustainable manufacturing.

The weighting of each indicator using the Best-Worst Method (BWM) is carried out through a systematic sequence of steps aimed at deriving optimal weights based on the decision-maker's preferences. The process begins by establishing a set of criteria $\{c_1, c_2, \dots, c_n\}$ which, in this context, represents the sustainability indicators aligned with the Triple Bottom Line (TBL) framework. Next, the decision-maker is asked to identify the most important criterion C_B and the least important criterion C_W from the predefined set of indicators. In the following step, the preference levels of the best criterion over all other criteria are determined using a comparison scale ranging from 1 to 9. This yields the best-to-others preference vector: $A_B = (a_{B1}, a_{B2}, \dots, a_{Bn})$, where a_{Bj} indicates how strongly criterion C_B is preferred over criterion j. Subsequently, the preferences of all criteria relative to the worst criterion are assessed, resulting in the others-to-worst preference vector: $A_w = (a_{1w}, a_{2w}, \dots, a_{nw})^T$, where a_{wj} represents the degree to which criterion j is preferred over the worst criterion C_W.

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Table 1. Formulas for assessing the performance of each indicator

No	Indicator	Input	Formula	Reference
1	Time (Menit)	TE = Time Efficiency VAT = Time in Value-Added Activities TT = Total Time NVAT = = Time in Non-Value-Added Activities n = process to n	$TE = \frac{VAT}{TT}$ $VAT = \sum_{i=1}^{n}(VATi)$ $NVAT = \sum_{i=1}^{n}(NVATi)$ $TT = VAT + NVAT$	[35]
2	Inventory (unit)	IE = Inventory Efficiency NI = Total Inventory TM = Total Materials	$IE = \frac{NI}{TM}$	[22]
3	Quality	QE = Quality Efficiency ND = Number of Defects TM = Total Material	$QE = 1 - \left(\frac{ND}{TM}\right)$	[36]
4	Cost (Rp)	CE = Cost Efficiency VAC = Costs in Value-Added Activities NVAC = Cost in Non-Value-Added Activities TC = Total Cost n = process to n	$CE = \frac{VAC}{TC}$ $VAC = \sum_{i=1}^{n}(VACi)$ $NVAC = \sum_{i=1}^{n}(NVACi)$ $TC = VAC + NVAC$	[35]
5	Material (kg)	ME = Material Efficiency VAM = Materials in Value-Added Activities TM = Total materials NVAM = Materials in Non-Value-Added Activities n = process to n	$ME = \frac{VAM}{TM}$ $VAM = \sum_{i=1}^{n}(VAMi)$ $NVAM = \sum_{i=1}^{n}(NVAMi)$ $TM = VAM + NVAM$	[35]
6	Energy (kWh)	EE = Energy Efficiency VAE = Energy in Value-Added Activities NVAE = Energy in Non-Value-Added Activities n = process to n	$EE = \frac{VAE}{TE}$ $VAE = \sum_{i=1}^{n}(VAEi)$ $NVAM = \sum_{i=1}^{n}(NVAEi)$ $TE = VAE + NVAE$	[35]
7	Water Consumption	WE = Water Efficiency AW = Amount of Water TW = Total Water	$WE = \frac{AW}{TW}$	[37]
8	Waste Recycle (kg)	TW = Total Waste WL = Amount of Land Waste	$WE = 1 - \frac{WL}{TW}$	[38]

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Table 1 Continued

No	Indicator	Input	Formula	Reference
9	Reuse of Products	TR = Total reuse WR = Number of reuses	$RE = 1 - \frac{WR}{TR}$	[22]
10	Satisfaction Level	TO = number of employee turnover NE = Total number of employees	$SE = 1 - \left(\frac{TO}{NE}\right)$	[22]
11	Health Level	NA = number of sick employees NE = Total number of employees	$HE = 1 - \left(\frac{NA}{NE}\right)$	[38]
12	Safety Level	NR= Number of activities at risk Nac = Total activity	$RE = 1 - \left(\frac{NR}{Nac}\right)$	[38]
13	Employee Training	E_HRD = Employee training level NT = Number of employees who attended the training NE = Total number of employees	$E_{HRD} = \frac{NT}{NE}$	[22]

Based on the two preference vectors, the optimal weights for each criterion are determined by minimising the maximum absolute deviation between the actual weights and the pairwise preference ratios. This ensures consistency between the decision-maker's qualitative judgments and the resulting quantitative weights. Mathematically, this optimisation problem is formulated as Model 1.

Model 1

$$\min \max\{|w_B - a_{Bj}w_j|, |w_j - a_{jw}w_w|\}$$

Subject to: $\sum_{j=1}^{n} w_j = 1, w_j \geq 0$

To simplify the solution process, Model 1 can be reformulated into a linear programming model, Model 2 by introducing a variable ξ which represents the smallest maximum absolute deviation. This transformation allows for a more tractable optimisation formulation, as shown below:

Model 2

$$\min \xi$$

Subject to: $\sum_{j=1}^{n} w_j = 1, w_j \geq 0$

$$|w_B - a_{Bj}w_j| \leq \xi$$
$$|w_j - a_{jw}w_w| \leq \xi$$

By solving Model 2, the optimal weights for each sustainability indicator, as well as the consistency ratio of the pairwise comparisons, are obtained. This process provides a robust and consistent framework for determining the relative importance of each indicator in assessing sustainable manufacturing performance. The derived weights

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ensure that the prioritisation of indicators reflects expert consensus while maintaining internal logical consistency, thereby enhancing the credibility and objectivity of the evaluation results.

Reliability assessment is essential following the completion of the indicator weighting process. In the context of the Best-Worst Method (BWM), the consistency level of decision-makers' pairwise comparisons can be evaluated using the maximum absolute deviation value ξ^* obtained from the solution of Model 2. This value reflects the degree of consistency in the preference judgments: the lower the value of ξ^*, the higher the consistency of the decision-making process. Conversely, a higher ξ^* indicates greater inconsistency in the judgments provided. To quantitatively assess this, Rezaei [34] proposed the use of a Consistency Ratio (CR), which is defined as can be seen in Equation (3).

$$CR = \frac{\xi^*}{Consistency\ Index} \quad (3)$$

In the Equation, ξ^* represents the maximum absolute deviation obtained from Model 2, while the Consistency Index (CI) refers to the highest reference value of ξ, derived from the most extreme preference comparison between the best criterion C_B and the worst criterion C_w, denoted by the preference value a_{BW}. The Consistency Ratio (CR) ranges between 0 and 1, with a value of CR ≤ 0.25 generally considered to indicate a high level of consistency in the weighting process. Once it is confirmed that the resulting weights meet the acceptable consistency threshold, the indicator weights obtained through the BWM method are subsequently used as importance values in assessing sustainable manufacturing performance.

The efficiency formulas for each of the 13 sustainability indicators utilised in this framework are detailed in Table 2. This table presents the calculation procedures required to evaluate the efficiency of each indicator systematically. The objective of this efficiency assessment is to provide a quantitative basis for measuring the actual performance of each sustainability indicator. Once the efficiency scores are obtained, the Manufacturing Sustainability Index (MSI) is calculated by multiplying each indicator's efficiency value by its corresponding weight, as determined through the BWM method [16]. The formula for calculating the MSI score is presented in Equation (4), where W_i denotes the weight of the i-th indicator, E_i is the efficiency score of the i-th indicator, and n represents the total number of indicators used Equation (4).

$$MSI = \sum_i^n Wi \cdot Ei \quad (4)$$

Additionally, the classification of MSI scores is performed using the Traffic Light System (TLS) approach, which is also applied in visualising indicator efficiency within the Sustainable Value Stream Mapping (Sus-VSM). The application of TLS in Sus-VSM visualisation enables decision-makers to identify indicators that require further attention. In this visualisation, red is used to indicate indicators with efficiency scores below 60%, signalling the need for immediate improvement. Yellow represents efficiency scores between 60% and 90%, indicating that the indicator still requires improvement to achieve optimal performance. Meanwhile, green indicates indicators with efficiency scores above 90%, signifying that the performance has met the expected sustainability targets. By applying the TLS principle, decision-makers can more easily formulate targeted improvement strategies to support the advancement of sustainable manufacturing performance.

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2.2 Case Study

The case study in this research focuses on the application of the Manufacturing Sustainability Assessment (MSA) in a coffee processing industry located in East Java, Indonesia. The selection of sustainability indicators was tailored to the company's actual operational conditions, aiming to analyse and improve the efficiency and sustainability of its production processes. The production stages in this company include: raw material reception, milling, washing, rewashing, drying, hulling, sifting, sorting, packaging, and storing. The relevance evaluation of the indicators was conducted using the Delphi method, involving three experts from both professional and industrial backgrounds in the coffee industry. These experts consisted of two senior managers with over ten years of operational experience in coffee processing and one academic specialising in sustainable manufacturing systems. The experts were selected based on their proven expertise in agro-industrial operations and active involvement in sustainability-related initiatives. The Delphi process was conducted using a structured questionnaire delivered via email, employing a 5-point Likert scale (1 = "very irrelevant" to 5 = "very highly relevant"), followed by clarification sessions to ensure consistency. These experts independently assessed the relevance level of each indicator, and the results are presented in Table 2.

Table 2. Results of the recapitulation of each indicator

Dimension	Indicator	Relevance					WA	LC
		1	2	3	4	5		
Economic	Time			1	5	4	4,3	0,9
	Inventory			2	4	4	4,2	0,8
	Quality		1	1	4	4	4,1	0,8
	Cost			2	5	3	4,1	0,8
Environmental	Material		1		6	3	4,1	0,9
	Energy			1	5	4	4,3	0,9
	Water Consumption			1	5	4	4,3	0,9
	Waste Recycle			2	4	4	4,2	0,8
	Reuse of products		1	5	2	2	3,5	0,4
Social	Satisfaction level			2	5	3	4,1	0,8
	Health level			2	5	3	4,1	0,8
	Safety level			2	4	4	4,2	0,8
	Employeee training			2	4	4	4,2	0,8

Subsequently, the three experts also participated in a Focus Group Discussion (FGD) session to identify the best and worst indicators within each dimension of the Triple Bottom Line (TBL). During this session, they were asked to determine the most important (best criterion) and least important (worst criterion) indicators based on their professional experience. The input gathered from this discussion was used to construct the two main vectors required in the BWM method: the Best-to-Others vector and the Others-to-Worst vector, as presented in Table 3 through Table 10. This collaborative approach ensured that the indicator weighting process was conducted with greater accuracy and consistency, taking into account the actual conditions of the coffee processing industry.

Table 3. Pairwise Comparison Matrix of TBL Dimensions – Best-to-Others

Best to Others	Economic	Environment	Social
Economic	1	4	2

Table 4. Pairwise Comparison Matrix of TBL Dimensions – Others-to-Worst

Others to the Worst	Environment
Economic	4
Environment	1
Social	2

Table 5. Pairwise Comparison Matrix of Economic Dimension – Best-to-Others

Best to Others	Time	Inventory	Quality	Cost
Quality	3	2	1	1

Table 6. Pairwise Comparison Matrix of Economic Dimension – Others-to-Worst

Others to the Worst	Time
Time	1
Inventory	2
Quality	3
Cost	3

Table 7. Pairwise Comparison Matrix of Environmental Dimension – Best-to-Others

Best to Others	Material	Energy	Water Consumption	Waste Recycle
Material	1	4	4	4

Table 8. Pairwise Comparison Matrix of Environmental Dimension – Others-to-Worst

Others to the Worst	Waste Recycle
Material	4
Energy	1
Water Consumption	1
Waste Recycle	1

Table 9. Pairwise Comparison Matrix of Social Dimension – Best-to-Others

Best to Others	Satisfaction Level	Health Level	Safety Level	Employee training
Safety Level	3	3	1	4

Table 10. Pairwise Comparison Matrix of Social Dimension – Others-to-Worst

Others to the Worst	Time
Satisfaction Level	2
Health Level	2
Safety Level	4
Employee Training	1

3. Results and Discussion

3.1 The evaluation of indicator weight

This section presents the results of weighting the dimensions and indicators of the Triple Bottom Line (TBL) using the Best-Worst Method (BWM). The weight values for each indicator are displayed in Table 11. The findings indicate that the Economic dimension received the highest weight, at 0.57, followed by the social dimension at 0.28, and the Environmental dimension at 0.14. These weights reflect the relative importance of each dimension in the context of sustainability within the coffee processing industry. The high weight assigned to the Economic dimension suggests that cost efficiency and product quality are the primary focus areas in implementing sustainability in this sector. This finding aligns with the study by [33], which identified economic and managerial barriers as the most significant obstacles to sustainability implementation in manufacturing industries, highlighting the critical role of the economic dimension in sustainability practices. The weighting process using BWM in this study underwent a consistency validation step, ensuring that the resulting weights are both consistent and reliable for use in assessing sustainable manufacturing performance.

Table 11. Indicator weights obtained through the BWM method

Dimension	Weight Dimension	Indicator	Weight Indicators	Global Weight
Economic	0.57	Time	0.11	0.06
		Inventory	0.19	0.11
		Quality	0.35	0.20
		Cost	0.35	0.20
Environment	0.14	Material	0.57	0.08
		Energy	0.14	0.02
		Water Consumption	0.14	0.02
		Waste Recycle	0.14	0.02
Social	0.28	Satisfaction level	0.19	0.05
		Health level	0.19	0.05
		Safety level	0.51	0.14
		Employee training	0.12	0.03

In addition, Table 11 presents the weights of sustainability indicators within each dimension. The results reveal that the Quality indicator holds the highest global weight, at 0.20, underscoring the critical importance of maintaining product quality in achieving sustainable manufacturing. High product quality not only enhances customer satisfaction but also contributes to improved process efficiency and reduced waste. The Cost indicator also plays a significant role, with a global weight of 0.20, reflecting the importance of efficient cost management in supporting the company's financial sustainability and improving its competitiveness. Furthermore, the Safety Level indicator from the social dimension shows a relatively strong influence, with a global weight of 0.14, indicating that occupational safety is a primary concern for ensuring operational sustainability and workforce well-being. These findings suggest that quality, cost, and safety are fundamental elements underlying the achievement of sustainability goals in the context of the coffee processing industry.

Based on these findings, the quality indicator in sustainable manufacturing deserves particular attention due to its substantial influence on overall sustainability performance. High-quality products not only enhance customer satisfaction but also support process efficiency, reduce waste, and strengthen the company's long-term reputation [39]. Additionally, the cost indicator plays a crucial role in supporting a company's financial sustainability. Effective cost management can serve as a critical foundation for optimising resource utilisation, minimising waste, and sustainably increasing profitability [7, 40]. Furthermore, workplace safety, reflected in the safety level indicator, must not be overlooked. A safe working environment not only protects employee health but also enhances productivity and fosters a stable, sustainable working condition [41]. By integratively focusing on these three key indicators — quality, cost, and safety — in manufacturing industries, particularly in the coffee processing sector, companies can reinforce their efforts in achieving sustainability across the entire production chain.

3.2 Sustainable value stream mapping (Sus-VSM)

This section presents the production line mapping based on the Sustainable Value Stream Mapping (Sus-VSM) approach, as illustrated in Figure 2. The mapping visualises the sustainability performance at each workstation based on the efficiency of the predefined indicators. The visualisation results reveal that several indicators, particularly those related to the time and inventory dimensions, still exhibit low efficiency levels. For the time indicator, four production stages fall below the performance threshold: receiving (53.7%), washing (46.2%), packaging (35.7%), and storing (40%), all of which are categorised as low-performing. Additionally, the inventory indicator reveals extremely low efficiency in the receiving process, with a score of only 14%. These findings suggest that process speed and inventory management at multiple workstations require critical attention to improve manufacturing sustainability in the coffee processing industry. Low efficiency in time and inventory indicators can directly lead to production delays, material buildup, and resource waste. Therefore, improvement efforts should focus on enhancing time management and material flow governance, such as through schedule optimisation, reduction of waiting times, or automation in critical processes. Moreover, data-driven decision-making is essential for identifying the root causes of underperformance at specific stages. With the implementation of these targeted improvements, it is expected that the sustainability performance across the entire production chain can be significantly enhanced.

3.3 Performance Score for Sustainable Manufacturing

This section presents the sustainable manufacturing performance score represented by the Manufacturing Sustainability Index (MSI). Based on the assessment results shown in Table 12, the coffee processing industry's sustainability performance achieved an MSI score of 80.95%. This score is categorised as fairly good, indicated by the colour yellow in the Traffic Light System (TLS), suggesting that although the overall performance is relatively high, there is still room for improvement. The contribution distribution to the MSI across the TBL dimensions reveals that the economic dimension contributed the most, followed by the social and then the environmental dimension. The high contribution from the economic dimension reflects the company's focus on cost efficiency and product quality. On the other hand, while the environmental indicators demonstrated relatively high efficiency scores, their overall contribution to the MSI remained low due to their small global weights. Meanwhile, the social dimension made a moderate contribution, although certain indicators, such as workplace safety, still require greater attention. These findings highlight the need for improvements in both the social and environmental aspects to achieve a more balanced and optimal sustainable manufacturing performance.

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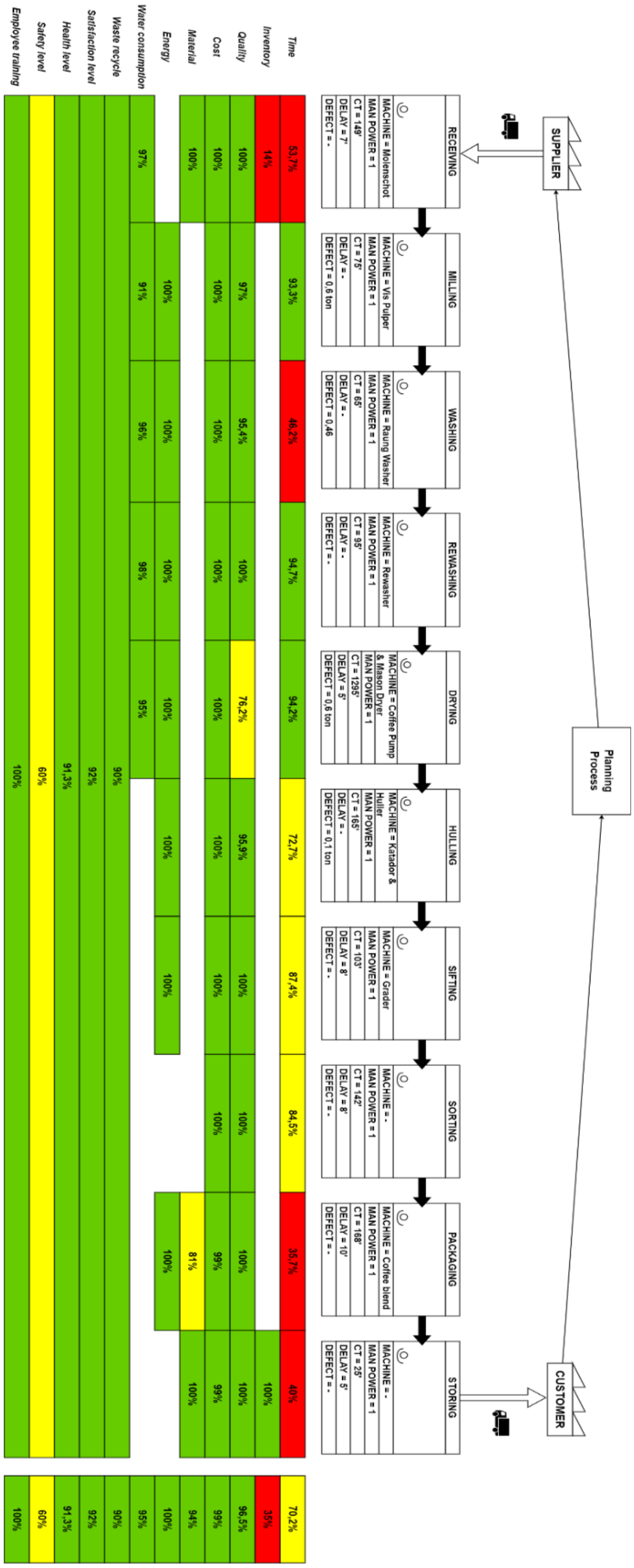

Figure 2. Mapping results of Sus-VSM in a case study of the coffee agro-industry

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Table 12. MSI Assessment Result

Dimension	Indicator	Efficiency Score (%)	Global Weight	Dimension Index (%)	MSI
Economic	Time	70.2	0.06	47.16	80.95
	Inventory	35	0.11		
	Quality	96.5	0.2		
	Cost	99	0.2		
Environment	Material	94	0.08	13.22	
	Energy	100	0.02		
	Water Consumption	95	0.02		
	Waste Recycle	90	0.02		
Social	Satisfaction level	92	0.05	20.57	
	Health level	91.3	0.05		
	Safety level	60	0.14		
	Employeee training	100	0.03		

In this study, the environmental aspect received the least attention among the three sustainability dimensions, accounting for only 13.22% of the overall MSI score. This is notable given that environmental sustainability is fundamental to the long-term viability of manufacturing operations, particularly in terms of resource efficiency, regulatory compliance, and environmental impact mitigation [42]. Although individual environmental indicators such as energy use, material efficiency, and water consumption achieved relatively high efficiency scores, their low global weights indicate that environmental considerations are not yet central to the company's sustainability strategy. This underrepresentation may reflect a limited strategic emphasis on environmental performance compared to economic outcomes.

To strengthen future sustainability initiatives, the company should consider rebalancing its priorities by integrating environmental goals into its core operational and investment strategies. Prioritising sustainable practices, such as waste minimisation, closed-loop material usage, and cleaner production technologies, can enhance resilience, improve stakeholder trust, and ensure compliance with increasingly stringent environmental standards. Moreover, as environmental performance becomes a key differentiator in global markets, embedding environmental objectives within strategic planning will not only reduce long-term operational risks but also create opportunities for innovation, market expansion, and enhanced corporate reputation [22, 43].

3.4 Research Implication

This study makes a significant theoretical contribution to the field of sustainable manufacturing performance evaluation. It integrates sustainability indicators across the three core dimensions of the Triple Bottom Line —economic, environmental, and social — thereby reinforcing a multidimensional approach to sustainability assessment. The application of the Best-Worst Method (BWM) for weighting indicators adds considerable value, as this method remains underutilised in the context of sustainable manufacturing. BWM offers advantages in terms of consistency and efficiency in multi-criteria decision-making, providing a more robust weighting structure compared to conventional methods, such as the Analytic Hierarchy Process (AHP). Furthermore, this study introduces a novel contribution by applying the proposed framework to the coffee agro-industry. This sector

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has received limited attention in sustainability research. As such, the framework not only enriches theoretical and methodological advancements but also opens new avenues for future exploration in underrepresented industrial sectors.

From a managerial standpoint, the findings of this study are highly relevant for managers and decision-makers aiming to improve sustainable manufacturing performance in the coffee processing industry. The results indicate that specific indicators, particularly time efficiency and inventory efficiency, continue to perform at low levels. These inefficiencies point to underlying issues in production time management and inventory systems. To address these challenges, it is recommended that companies develop and implement Standard Operating Procedures (SOPs) focused on reducing waiting times and improving material flow [44]. Additional improvement measures may include streamlining work processes, optimising production schedules, and adopting digital monitoring systems to enable real-time control of operations. It is also crucial for companies to establish realistic and measurable efficiency targets, while avoiding excessive pressure that could disrupt the stability of their supply chains. Inventory performance can be further enhanced through demand-driven inventory systems and closer collaboration with raw material suppliers [45]. By adopting these strategies, companies are expected to improve overall process efficiency and strengthen sustainable manufacturing performance within the coffee agro-industry.

4. Conclusion

This study introduces a novel approach to evaluating sustainable manufacturing performance by integrating the Delphi method, Best-Worst Method (BWM), and Sustainable Value Stream Mapping (Sus-VSM). The proposed framework encompasses the selection of indicators using the Delphi method, determination of indicator weights through the BWM, calculation of efficiency for each indicator, and visualisation of efficiency results via Sus-VSM mapping and classification using the Traffic Light System (TLS). Through this approach, the Manufacturing Sustainability Index (MSI) can be comprehensively determined by considering both the weights and performance of individual indicators. The application of this framework in the Indonesian coffee processing industry yielded a sustainability score of 80.95%, which is categorised as high. However, the results also reveal opportunities for improvement, particularly in the environmental dimension and several social indicators.

This study provides a significant methodological contribution to the assessment of sustainable manufacturing. The successful application of the proposed framework in the coffee agro-industry sector demonstrates its potential for broader implementation across other manufacturing sectors. Furthermore, the identification of indicators with low efficiency offers a foundation for more targeted interventions aimed at improving sustainability practices at the operational level. Nevertheless, this study has certain limitations. It is based on a single case study within the coffee processing industry. It does not account for potential interdependencies among sustainability indicators that may influence one another. Therefore, future research could enhance the proposed framework by integrating the relationships between indicators to achieve a more holistic assessment. Moreover, the scope of the study can be broadened by conducting cross-sector case studies within the manufacturing industry and by incorporating a wider range of sustainability indicators. Such developments would strengthen the assessment procedure and provide a more comprehensive understanding of sustainable manufacturing practices.

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Declarations

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