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Research Article

Enhanced Sustainability Assessment Framework for Plywood Manufacturing: A Multi-Method Approach Using Delphi Technique, BWM, and S-VSM

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ABSTRACT

Sustainable manufacturing has emerged as a critical priority in addressing the complex environmental, social, and economic challenges of modern industry. This study focuses on the plywood sector, a significant contributor to manufacturing, which faces distinct sustainability issues such as high energy consumption, material inefficiencies, and hazardous working conditions. To address these challenges, the research introduces workload and noise level as critical indicators for assessing sustainability, broadening the scope of traditional evaluation methods. A multi-method framework was employed, integrating the Delphi technique to identify key sustainability indicators, the Best Worst Method (BWM) to assign weights to these indicators, and Sustainable Value Stream Mapping (S-VSM) paired with a Traffic Light System (TLS) to evaluate and visualize the Manufacturing Sustainability Score (MSS). Applied to a plywood manufacturing case study, the framework highlighted areas requiring improvement, particularly in worker well-being and operational safety, while demonstrating the industry's moderate overall efficiency. By offering actionable insights for improving resource use, operational processes, and employee conditions, this framework provides a practical tool for industry managers aiming to enhance sustainability. Furthermore, its adaptability makes it a valuable reference for other manufacturing sectors seeking to implement resource-efficient and sustainable practices. This research not only fills critical gaps in sustainability assessment but also contributes to advancing industry practices by emphasizing holistic and innovative approaches to manufacturing efficiency.

Keywords: Sustainability assessment framework, plywood manufacturing, Delphi, BWM, S-VSM

INTRODUCTION

Environmental sustainability has become a growing concern in the manufacturing industry and across various aspects of human existence [1]. The heightened focus on sustainability is driven by the substantial environmental and societal impacts of manufacturing and logistics operations, including air and water pollution [2], [3]. To address these challenges, companies must transition toward sustainable operations and adopt business models aligned with circular economy principles [4]. This transformation is particularly critical for the plywood industry, which faces distinct challenges such as high energy consumption, risks to raw material availability due to deforestation, and suboptimal workplace conditions caused by excessive noise and dust [5]. Addressing these issues is essential not only for regulatory compliance but also for ensuring the long-term sustainability of the industry and safeguarding worker well-being [6]. Given its direct impact on natural resource management and community health, sustainability in this sector holds significant importance. Lean manufacturing principles, aligned with the Triple Bottom Line (TBL) framework, offer a promising strategy to enhance performance across economic, environmental, and social dimensions, thereby advancing long-term sustainability goals [7], [8].

The Manufacturing Sustainability Assessment (MSA) framework is widely recognized for evaluating sustainability in manufacturing. Over the past decade, substantial progress has been made in developing such frameworks, with the Triple Bottom Line (TBL) framework emerging as a foundational approach that integrates economic, environmental, and social dimensions [8]. Elkington [9] first proposed the concept of sustainability assessment through the TBL framework, which was later recognized by Rogers and Hudson [10] as an essential indicator of sustainable development. Table 1 provides an overview of prior studies utilizing the TBL framework in the context of sustainable manufacturing.

Despite its broad applicability, the TBL framework often struggles to address the unique and complex challenges faced by resource-intensive industries like plywood manufacturing. These challenges include high energy demands, dependence on raw materials, and workplace-specific factors such as noise exposure and excessive workloads [11]. The framework's general nature limits its ability to comprehensively evaluate sustainability impacts in these sectors, highlighting the need for more tailored approaches. While prior studies—such as those by Huang and Badurdeen [12], Hartini et al. [13], and Mubin et al. [8]—have addressed sustainability in manufacturing, critical indicators like workload and noise remain underexplored. Incorporating these factors is essential for developing more comprehensive frameworks to effectively support sustainable practices, particularly in resource-intensive industries.

Table 1. Literature Review of Manufacturing Sustainability Research

Study	MSA	Aspect			Indicator Weight	Workload	Noise Level	Application	Tools
		Economic	Environment	Social					
Banawi and Bilec [22]	-	√	-	-	-	-	-	Construction industry	LCA, VSM
Paju, et al. [27]	-	√	-	-	-	-	-	Not Clear	LCA, VSM
Brown, et al. [19]	-	√	√	√	-	-	-	Electronic	VSM
Faulkner and Badurdeen [21]	√	-	√	√	-	-	-	Manufacturing	Sus-VSM
Huang and Badurdeen [12]	√	√	√	√	-	-	-	Electronics	AHP
Garza-Reyes, et al. [28]	-	-	-	√	-	-	-	Manufacturing	PDCA, VSM
Hartini, et al. [13]	√	√	√	√	-	-	-	Furniture	Delphi, AHP, VSM
Soltani, et al. [29]	-	√	√	√	-	-	-	Gas Bottle	AHP, VSM, TOPSIS
Castiglione, et al. [30]	-	√	-	√	-	-	-	Manufacturing	MEIO
Bhadu, et al. [31]	√	√	-	-	-	-	-	Manufacturing	AHP
Utama, et al. [3]	√	√	√	√	√	-	-	Furniture	Delphi, Dematel – ANP, VSM
Mubin, et al. [8]	√	√	√	√	√	√	-	Plastic Industry	AHP, Sus-VSM
Dewi, et al. [26]	√	√	√	√	√	√	-	Tire Industry	Delphi, AHP, Sus-VSM
Utama and Abirfatin [18]	√	√	√	√	√	√	-	Carrageenan Industry	Sus-Lean Six Sigma
This Research	√	√	√	√	√	√	√	Plywood Industry	Delphi, BWM, S-VSM

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Significant gaps remain in the evaluation of social factors, especially those related to mental load, physical workload, and noise levels [3], [13]. Most research has primarily focused on economic, environmental, and basic social aspects, neglecting these specific indicators [14]-[16]. For instance, while Mubin et al. [8] included workload indicators in their evaluation of manufacturing sustainability, they did not address noise levels. Conversely, Bolaji et al. [17] emphasized the importance of assessing noise levels, noting their critical role in sustainable manufacturing. Including such assessments helps mitigate the detrimental effects of industrial noise on environmental sustainability and human well-being, addressing a crucial dimension of sustainability.

Building on these identified gaps, this study focuses on the plywood industry, a key manufacturing sector with unique sustainability challenges. The industry's heavy reliance on natural resources exposes it to environmental and social sustainability concerns, including deforestation, high energy consumption, and unsafe workplace conditions. Despite its significant ecological footprint and the critical importance of worker safety, the plywood sector has received limited attention in sustainability research compared to industries like furniture [15], carrageenan [18], electronics [19], and plastics [8]. This discrepancy underscores the urgent need for focused research in the plywood sector. To address this gap, the study integrates workload and noise level indicators into the sustainability assessment framework, considering not only traditional aspects such as production efficiency, material use, and emissions but also their impacts on worker well-being and the environment.

Integrating Value Stream Mapping (VSM) with sustainability assessment tools represents a significant advancement in sustainable manufacturing. VSM has been widely adopted to evaluate manufacturing processes from a sustainability perspective [20]. Recent developments, such as Sustainable Value Stream Mapping (S-VSM), have introduced an organized approach that incorporates economic, environmental, and social indicators, as demonstrated by Faulkner and Badurdeen [21]. S-VSM addresses key operational challenges in resource-intensive industries, including material waste, high energy consumption, and workplace issues such as noise and excessive workload. By systematically identifying inefficiencies across TBL dimensions, S-VSM provides actionable insights for improving sustainability performance. This methodology is particularly relevant for addressing the complex sustainability requirements of the plywood industry.

Several approaches have been developed to assess sustainability in manufacturing. For example, Banawi and Bilec [22] applied Life Cycle Assessment (LCA) and VSM to analyze sustainability in the construction industry, primarily focusing on economic aspects. Hartini et al. [16] combined the Delphi method, Analytical Hierarchy Process (AHP), and VSM to evaluate sustainability in the furniture industry, considering economic, environmental, and social aspects. Utama et al. [3] introduced a comprehensive framework that integrates DEMATEL and the Analytic Network Process (ANP) to assess sustainability performance based on weighted indicators. However, as summarized in Table 1, these approaches often fail to address sector-specific challenges, such as workload and noise levels, unique to the plywood industry. Conventional tools like LCA and AHP are insufficient for capturing these complexities, emphasizing the need for tailored frameworks that incorporate both traditional and underrepresented indicators.

This study proposes a novel framework that addresses underexplored aspects of sustainable manufacturing, including workload and noise levels. The framework integrates the Delphi method, Best Worst Method (BWM), Sustainable Value Stream Mapping (S-VSM), and the Traffic Light System (TLS) to comprehensively evaluate sustainability. The Delphi method ensures the inclusion of context-specific sustainability indicators through expert consensus, systematically incorporating factors such as workload and noise [23]. BWM enhances this process by assigning consistent and efficient weights to the identified indicators, outperforming AHP in terms of consistency and decision-making efficiency [24], [25]. The TLS principle facilitates the visualization of sustainability performance through S-VSM, highlighting key areas for improvement and providing actionable insights. The Manufacturing Sustainability Score (MSS) is then computed by combining these indicator weights with performance metrics, offering a holistic evaluation of sustainability. By integrating these methodologies, the proposed framework not only supports practitioners in enhancing sustainability but also fosters further exploration of integrating VSM with sustainability indicators in manufacturing practices.

METHODS

Proposed Framework for Assessing Manufacturing Sustainability

The proposed framework for evaluating performance in sustainable manufacturing practices is presented in this section. Figure 1 shows the proposed MSA framework. The proposed MSA framework for sustainable manufacturing includes three stages: indicator selection, weighting, and mapping. In the first stage, the Delphi method identifies relevant indicators covering economic, social, and environmental dimensions, considering plywood-specific challenges such as workload and noise levels [32]. The second stage uses the best-worst method (BWM) to prioritize these indicators through consistent and reliable weighting, addressing critical issues like resource efficiency and workplace conditions [33]. Finally, Sustainable Value Stream Mapping (S-VSM) is used to visualize sustainability

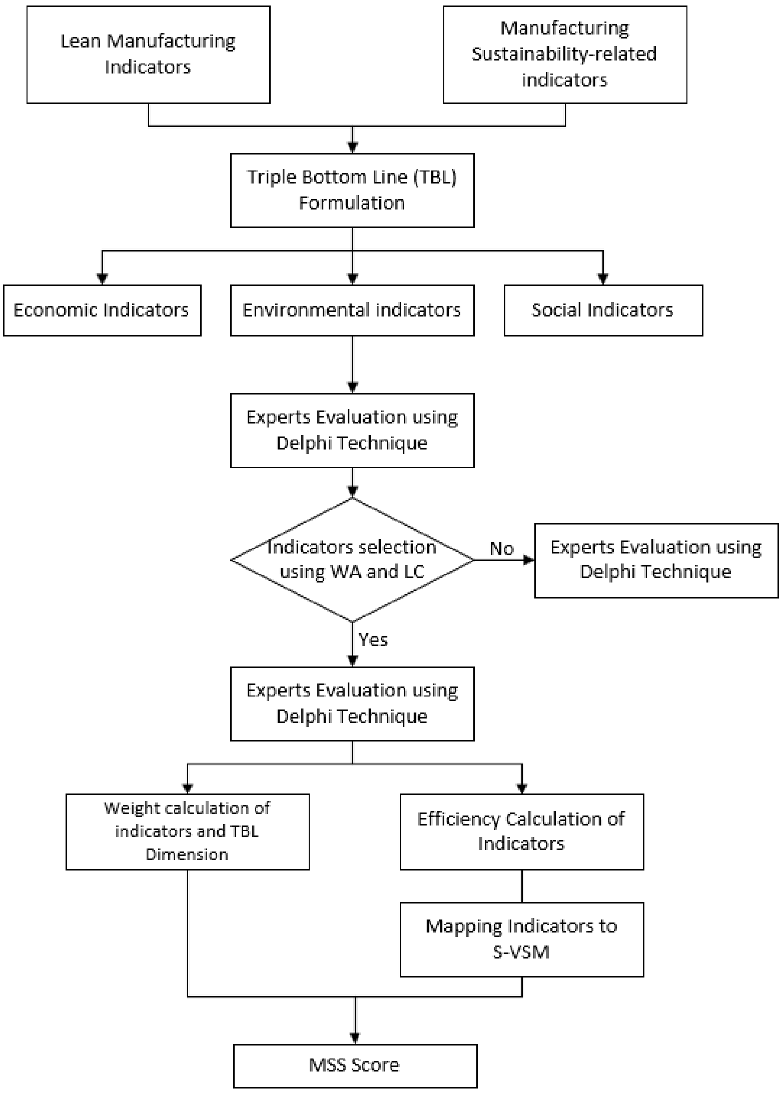

Figure 1. Framework proposed for sustainability performance in manufacturing

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performance, identify inefficiencies, and guide targeted improvements in the resource-intensive processes of plywood manufacturing.

The proposed framework employs the Delphi method to identify quantitative and qualitative indicators, ensuring their reliability and validity for the plywood industry. This method was chosen for its structured approach to achieving expert consensus, which is essential for addressing unique industry challenges like workload and noise levels that are often overlooked in traditional assessments [23]. By involving expert opinion, the Delphi method ensures that the selected indicators are contextually relevant and aligned with the specific sustainability requirements of the plywood industry.

The average method is employed in the Delphi approach to ensure the significance of indicators about company sustainability [34]. Expert evaluations on sustainable manufacturing indicators are calculated using the Level of Consensus (LC) and Weight Average (WA) techniques [34],[35]. According to Hartini, et al. [13], indicators for sustainable manufacturing performance are deemed significant when they exhibit LC values of ≥ 0.7 and WA values of ≥ 4.0. Equations (1) and (2) represent the formulations for WA and LC. FNR represents the number of respondents providing relevant responses, while SR_i indicates the relevance assessment score given by the i-th respondent. The symbol Nr denotes the total number of respondents. The questionnaire used in the Delphi method to evaluate the relevance of indicators employs a rating scale ranging from 1 to 5, where a rating of 1 signifies insignificance and 5 signifies an exceptionally high level of significance.

$$WA = \frac{\sum SR_i}{Nr} \tag{1}$$

$$LC = \frac{FNR}{Nr} \tag{2}$$

In the next stage, efficiency calculations are performed for each relevant indicator, and indicator mapping is conducted using S-VSM for MSA evaluation. The selected indicators' efficiency is calculated using the formula specified in Appendix, considering workload and noise level indicators in manufacturing sustainability within the social aspect. The indicators are linked to specific sustainability goals. Workload helps improve workers' well-being and productivity, while noise levels focus on workplace safety and health. The Mental Load Index is measured using the Rating Scale Mental Effort (RSME) developed by Van Doorn and Zijlstra [36], a method recognized for its simplicity, speed, and reliability in evaluating mental effort. This method is instrumental in identifying workload-related issues that might affect sustainable performance. Widyanti, et al. [37], highlight the efficiency and practicality of RSME in pinpointing workload factors, making it a valuable addition to sustainability assessments. Similarly, evaluating noise levels is critical for mitigating exposure risks, enhancing workplace safety, and advancing broader sustainability objectives by addressing social and environmental concerns effectively.

These indicators are prioritized using the Best Worst Method (BWM), chosen for its efficiency, simplicity, and superior consistency in comparison to methods like the Analytical Hierarchy Process (AHP) [25],[38]. Unlike traditional approaches, BWM minimizes redundancy by focusing only on the most and least important criteria, ensuring more reliable outcomes in complex decision-making contexts [39]. The method employs a 1–9 scale for paired comparisons to evaluate the relative importance of each indicator, with higher scores representing greater priority [40]. In this study, the paired comparisons were carried out through a Focus Group Discussion (FGD) involving experts to establish a consensus on the priority levels of the indicators, ensuring their contextual relevance and alignment with sustainability goals.

Assigning weights to criteria in BWM involves five stages [39]. By employing the same method, alternative weights for each criterion can be determined. Therefore, our attention is focused on resolving the process related to determining criterion weights. The following outlines the five steps of BWM.

Step 1. Establishment of a collection of decision and finalizing criteria. $\{c_1, c_2, \ldots, c_n\}$ represent the finalized criteria.
Step 2. Among the set of decision criteria, select the best criterion C_B and worst criterion C_W. In situations where multiple best and worst criteria exist, the choice of the best and worst criteria may be left to chance.
Step 3. Preference determination of the best criterion relative to all other criteria, employing a nine-point scale. The vector denoting the preference of the best criterion over all other criteria is denoted by $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$. The symbol a_{Bj} denotes the degree of preference that criterion B has over criterion j. Specifically, $a_{BB} = 1$.
Step 4. Preference determination of the worst criterion relative to all other criteria, employing a nine-point scale. The preference of all other criteria over the worst criterion is represented by the others-to-worst vector, denoted by $A_w = (a_{1w}, a_{2w}, \ldots, a_{nw})^T$. The symbol a_{wj} denotes the degree to which criterion j is preferred over the worst criterion w. Specifically, $a_{ww} = 1$.
Step 5. Determining the optimal weights for criteria $(w_1^*, w_2^*, \ldots, w_n^*)$
The aim is to identify the optimal weights that have the maximum absolute difference between $\{|w_B, -a_{Bj}w_j|, |w_j - a_{jw}w_w|\}$, minimized for all j. The following model is generated, considering the weight summation and non-negativity constraints.

Model 1

$$\min \max\{|w_B - a_{Bj}w_j|, |w_j - a_{jw}w_w|\}$$
$$s.t. \sum_{j=1}^{n} w_j = 1, w_j \geq 0, j = 1,2, \ldots, n$$

By using ξ to represent the smallest absolute difference, Model 1 can be equivalently transformed into Model 2.

Model 2

$$\min \xi$$
$$s.t. \sum_{j=1}^{n} w_j = 1, w_j \geq 0, j = 1,2, \ldots, n$$
$$|w_B - a_{Bj}w_j| \leq \xi$$
$$|w_j - a_{jw}w_w| \leq \xi$$

From a mathematical perspective, the solution space of Model 1 may become non-empty when the value of ξ approaches a sufficiently large magnitude. By solving Model 2, it was possible to derive the weights of the criteria and the corresponding maximal absolute difference. A summary of the five BWM phases is presented in Figure 2. The

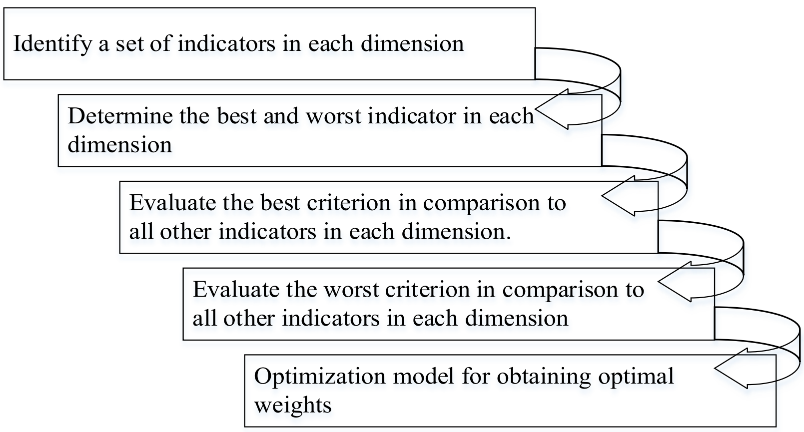

Figure 2. The five-step BWM procedure

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assessment of result reliability should be conducted subsequent to the determination of criterion weights. Deriving the Consistency Ratio (CR) is possible with the maximal absolute difference ξ^*, which is obtained from Model 2. Comparative reliability is intuitively diminished as the value of ξ^* increases. Rezaei [39] introduced the following CR formula for the BWM:

$$CR = \frac{\xi^*}{Consistency\ Index} \tag{3}$$

where ξ^* represents the maximum absolute difference derived from Model 2 and $CR \epsilon [0,1]$. The Consistency Index, represented as ξ_{max}, signifies the highest value of ξ obtained by determining the criterion with the greatest preference degree a_{Bw} of criterion C_B over criterion C_w. Subsequently, in the MSA, the indicator weights acquired through the BWM method are implemented as importance scores.

The efficiency formulas for each of the 11 indicators provided in the proposed framework are detailed Appendix A.1. The table provides a summary of the steps required to evaluate the effectiveness of each indicator. The objective of evaluating indicator efficiency is to provide a systematic and objective assessment using these formulas. The MSA value is obtained by multiplying the indicator efficiency by its weight [12]. The calculation formula for MSA is represented by equation (4), where W_i denotes the weight of indicator i calculated using the BWM method, and E_i represents the efficiency score of indicator i. n indicates the number of indicators.

$$MSA = \sum_i^n Wi \cdot Ei \tag{4}$$

The classification of MSA scores is also conducted by applying the TLS principle, which is likewise utilized to map the efficiency of sustainable manufacturing indicators in S-VSM.

The integration of TLS into S-VSM and MSA classification helps decision-makers evaluate sustainable manufacturing indicators on the production line. This visualization highlights which indicators need improvement. The mapping of sustainable manufacturing indicators uses three colors. Indicators of sustainable manufacturing that have an efficiency value below 60% are highlighted in red, indicating an urgent need for performance enhancement. Conversely, a value ranging from 60% to 90% efficiency is denoted by the yellow color, which signifies that the performance of indicators related to sustainable manufacturing must be improved in order to attain the most favorable outcomes. However, green-colored indicators become visible when the efficiency value exceeds 90%, signifying that the indicators have successfully executed the intended functions and outcomes. This classification system helps decision-makers prioritize resources and actions effectively, focusing on critical issues first while maintaining high-performing areas.

Case Implementation

This study investigates the implementation of sustainable manufacturing practices within the plywood industry in Samarinda, Indonesia, emphasizing key sustainability challenges such as high energy consumption, material waste, and workplace conditions, including noise and workload. The identified indicators, focusing on workload and noise levels, are specifically designed to address these challenges. As described in the previous section, these indicators aim to evaluate and enhance efficiency and sustainability in the work environment. For example, excessive workload during the rotary and press stages affects worker well-being, while elevated noise levels during the log cutting and rotary stages pose significant health risks. The plywood manufacturing process is divided into 13 distinct stages: log cutting, rotary, clipper, dryer, composer, setting, glue, press, sizer, putty, sander, grading, and packaging. Among these, stages such as rotary, press, and dryer are the most critical in terms of sustainability, due to their high energy demands, noise emissions, and workload intensity.

To evaluate and validate the chosen indicators, the Delphi method was employed. A questionnaire was distributed to a panel of eight industry experts, including professionals in key roles such as plant manager, production manager, PPIC manager, FAD manager, general maintenance manager, logistics manager, finance manager, and resin plant manager. These experts were selected based on their extensive experience, with each holding senior management positions for over five years. Their collective expertise provides a comprehensive perspective on the operational and sustainability challenges faced by the company. The results of this evaluation are summarized in Table 2.

Eight experts also participated in a Focus Group Discussion (FGD) to identify the best and worst factors for each dimension of the Triple Bottom Line (TBL). Following the FGD, the experts were asked to indicate which factors they considered the best and worst indicators for sustainable manufacturing in the plywood industry. The input from these experts contributed to the formulation of the Best-to-Others vector and Others-to-Worst vector, which are presented in Tables 3-10 The involvement of these experts significantly enhanced the accuracy of the Best Worst Method (BWM) weighting process. Their extensive knowledge and hands-on experience within the plywood industry ensured that the assigned weights accurately reflected real-world conditions and priorities. The collaborative nature of the Focus Group Discussion (FGD) also helped minimize subjectivity and bias, leading to a more consistent and reliable evaluation of the indicators. This high level of precision is crucial for addressing the specific sustainability challenges of the plywood industry, including workload, noise levels, and resource efficiency.

Table 2. Summary of the outcomes for each indicator

Dimensions	**Indicators**	**Relevance**					WA	**LC**
		1	**2**	**3**	**4**	**5**		
Economic	Time Efficiency	-	-	1	3	3	3.8	0.8
	Quality Efficiency	-	-	2	4	2	4	0.8
	Inventory Efficiency	-	-	1	3	4	4.4	0.9
	Cost Efficiency	-	-	1	2	5	4.5	0.9
Environment	Material Efficiency	-	-	1	4	3	4.3	0.9
	Energy Efficiency	-	-	1	4	3	4.3	0.9
	Efficiency of Waste Recycle	-	-	1	6	1	4	0.9
Social	Physical load index Efficiency	-	-	2	3	3	4.1	0.8
	Mental workload Efficiency	-	-	2	2	4	4.3	0.8
	Safety Level	-	-	2	3	3	4.1	0.8
	Noise level	-	-	2	4	2	4	0.8

Table 3. Pairwise comparison of TBL dimensions for Best-to-Others

Best to Others	**Economic**	**Environment**	**Social**
Economic	1	3	7

Table 4. Pairwise comparison of TBL dimensions for Others-to-Worst

Others to the Worst	**Social**
Economic	5
Environment	3
Social	1

Table 5. Pairwise comparison of Economic Indicators for Best-to-Others

Best to Others	**Time Efficiency**	**Cost Efficiency**	**Quality Efficiency**	**Inventory Efficiency**
Time	1	3	4	7

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Table 6. Pairwise comparison of Economic Indicators for Others-to-Worst

Others to the Worst	**Inventory**
Time Efficiency	7
Cost Efficiency	4
Quality Efficiency	3
Inventory Efficiency	1

Table 7. Pairwise comparison of Environment Indicators for Best-to-Others

Best to Others	**Material Efficiency**	**Energy Efficiency**	**Efficiency of Waste Recycle**
Waste Recycle	2	1	1

Table 8. Pairwise comparison of Environment Indicators for Others-to-Worst

Others to the Worst	**Material**
Material Efficiency	1
Energy Efficiency	2
Efficiency of Waste Recycle	2

Table 9. Pairwise comparison of Social Indicators for Best-to-Others

Best to Others	**Safety Level**	**Physical load index Efficiency**	**Noise Level**	**Mental workload Efficiency**
Safety Level	1	2	2	3

Table 10. Pairwise comparison of Social Indicators for Others-to-Worst

Others to the Worst	Mental Load
Safety Level	3
Physical load index Efficiency	2
Noise level	2
Mental workload Efficiency	1

RESULT AND DISCUSSION

Indicator Weight assessment analysis

This section presents the weighting results for the Triple Bottom Line (TBL) aspects and indicators using the Best Worst Method (BWM), as shown in Table 11. The data reveal that the economic dimension holds the highest weight (0.64), followed by the environmental (0.25) and social dimensions (0.11), reflecting the relative importance of each dimension in the context of TBL. The economic dimension ranks highest, attributed to the critical role of indicators such as time efficiency (0.36) and cost efficiency (0.14) in optimizing production processes and reducing operational costs. These findings align with Utama and Abirfatin [18], who emphasize the prominence of economic factors in sustainable manufacturing practices.

The environmental dimension (0.25) prioritizes indicators such as energy efficiency and waste recycling, each weighted at 0.10, highlighting the significance of resource conservation and waste management in sustainability

Table 11. Indicators of weight derived from BWM

Dimension	Weight Dimension	Indicator	Weight Indicators	Global Weight
Economic	0.64	Time Efficiency	0.56	0.36
		Quality Efficiency	0.16	0.10
		Inventory Efficiency	0.07	0.05
		Cost Efficiency	0.21	0.14
Environment	0.25	Material Efficiency	0.2	0.05
		Energy Efficiency	0.4	0.1
		Efficiency of Waste Recycle	0.4	0.1
Social	0.11	Physical load index Efficiency	0.23	0.02
		Mental workload Efficiency	0.13	0.01
		Safety Level	0.42	0.04
		Noise level	0.23	0.02

efforts. The social dimension (0.11) underscores the importance of worker well-being, with key indicators like safety level (0.04) and noise level (0.02) aimed at improving workplace conditions. The pairwise comparisons produced a consistency ratio of 0.047, ensuring the reliability and validity of the results.

In addition, Table 11 presents the indicator weights for each dimension. The findings reveal that time efficiency holds the highest weight (0.36), followed by cost efficiency (0.14) and quality efficiency (0.10). Time efficiency is identified as the most critical indicator, emphasizing its role in optimizing production output, reducing delays, and improving resource utilization [3]. In the plywood industry, time efficiency is particularly impactful on energy consumption and responsiveness to market demands, where timely production can significantly reduce energy use and enhance operational agility. Cost efficiency (0.14) highlights the importance of managing costs effectively to ensure financial sustainability and maintain competitiveness. By optimizing resource allocation and reducing waste, cost efficiency supports the industry's long-term economic viability [26]. Quality efficiency (0.10) is equally essential, as it ensures that the production meets established product standards, boosts customer satisfaction, and reduces waste.

These findings underscore the importance of focusing on the time efficiency in sustainable manufacturing, as it significantly influences overall sustainability performance. In the context of the plywood industry, enhancing the time efficiency can be achieved by optimizing production processes. This could involve reducing production stages in rotary and sander, minimizing idle time, and implementing more effective scheduling systems to prevent delays [8, 45]. The cost efficiency also plays a critical role in sustainability. Practical steps to improve cost efficiency include reducing waste through better utilization of raw materials and implementing recycling practices. Additionally, investing in energy-efficient machinery can lead to significant cost savings and environmental benefits [41]. These strategies not only contribute to long-term profitability but also support ecological sustainability by minimizing waste and optimizing resource use [46].

In addition to time and cost indicators, quality indicators are also crucial for achieving sustainability in manufacturing. Product quality is not only central to meeting customer expectations but also enhances a company's reputation for reliability and adherence to sustainability standards [47]. Ensuring high product quality reduces defects and waste, contributing to both economic sustainability and customer satisfaction. Furthermore, addressing mental workload indicators is essential for improving productivity and ensuring long-term sustainability in the workforce. A manageable mental workload enables workers to maintain focus and efficiency, directly impacting an organization's financial performance [8]. Noise levels in the manufacturing environment are also a critical factor to consider. Prolonged exposure to high noise levels can result in hearing impairments, stress, fatigue, sleep disturbances, and other health problems among employees [48]. These health issues, in turn, negatively affect productivity and overall worker performance.

Analysis of Sustainable Value Stream Mapping (S-VSM)

This section presents the production line mapping using S-VSM, highlighting the efficiency and performance mapping outcomes through the traffic light system (see Appendix A.2). The results indicate that the mental workload and safety level indicators exhibit low efficiency values of 37.95% and 24.31%, respectively, marked in red across all workstations. These low scores emphasize areas for improvement in the plywood industry's social sustainability performance, particularly regarding employee well-being and overall workplace conditions. High mental workload is a critical factor as it can lead to worker fatigue, diminished focus, and a higher likelihood of mistakes, ultimately decreasing productivity and compromising safety [49]. Inadequate safety levels further exacerbate these issues, potentially leading to a hazardous working environment, higher turnover rates, and lower job satisfaction among employees [50]. To address these issues, the plywood industry could implement several strategies aimed at improving the mental workload and safety conditions. Stress management training can help workers cope with the pressures of their roles, while enhancing safety infrastructure can mitigate accident risks. Additionally, establishing proactive monitoring systems will allow the company to detect potential safety hazards before they lead to accidents or injuries [51]. These initiatives are essential for improving the social sustainability of the plywood industry, as they directly contribute to the health, safety, and overall well-being of employees, which in turn fosters a more productive and satisfied workforce.

Measurement results of Manufacturing Sustainability Score (MSS)

The MSS assessment results, as presented in Table 12, identify several crucial insights regarding the sustainable performance of the plywood industry. A key finding is that the industry has an MSS score of 80.27%, indicating that while sustainability efforts are underway, there is still room for improvement to meet optimal sustainable standards. The yellow signals in the TLS suggest that specific areas within the social and environmental dimensions require attention and further improvement. When broken down by the Triple Bottom Line (TBL) dimensions, the economic performance score is the highest, at 51.24%, indicating that economic sustainability is being somewhat effectively addressed. In contrast, the environmental dimension scores 23.80%, and the social dimension scores 5.24%, both

Table 12. The result of MSS assessment

Dimension	Indicator	Indicator Score	Global Weight	Indicator Index	Dimension Index	MSS
Economic	Time Efficiency	75.58	0.36	27.28	51.24	80.27
	Quality Efficiency	92.29	0.10	9.37		
	Inventory Efficiency	90.93	0.05	4.10		
	Cost Efficiency	77.50	0.14	10.49		
Environment	Material Efficiency	97.87	0.05	4.89	23.80	
	Energy Efficiency	96.79	0.1	9.68		
	Efficiency of Waste Recycle	92.26	0.1	9.23		
Social	Physical load index Efficiency	85.77	0.02	2.08	5.24	
	Mental workload Efficiency	37.95	0.01	0.53		
	Safety Level	24.31	0.04	1.09		
	Noise level	63.83	0.02	1.55		

reflecting a significant gap in their contributions to overall sustainability. These findings align with those reported by Hartini, et al. [13], highlighting the need for targeted improvements in these two dimensions. While there is no specific global benchmark for plywood manufacturing, the MSS score of 80.27% suggests that the industry is performing above average when compared to other resource-intensive industries that face similar sustainability challenges. However, further comparisons with broader industrial benchmarks or global sustainability targets would offer a more comprehensive understanding of the plywood industry's standing in the global sustainability landscape.

In this study, the economic dimension demonstrates higher performance with a score of 51.24%, reflecting the plywood industry's effectiveness in addressing key economic aspects such as improved productivity, operational efficiency, and cost management. The adoption of advanced technologies, efficient resource management, and successful marketing strategies have contributed significantly to these achievements. However, the social dimension is notably underperforming with a low score of 5.24%, highlighting critical gaps in workplace conditions and employee well-being. This low performance highlights a need for urgent attention to social aspects, as poor working conditions—such as high mental workload and inadequate safety measures—can negatively affect employee morale, health, and productivity. These issues can lead to higher turnover rates and increased absenteeism, which ultimately impact the industry's overall performance [52, 53].

On the environmental dimension, the plywood industry performs moderately with a score of 23.80%. While there are some efforts to improve energy efficiency and implement waste recycling initiatives, these actions require further emphasis and improvement to reach a high level of sustainability. Increased focus on resource conservation, sustainable practices, and reducing environmental impact is necessary to improve performance in this area. Overall, while the plywood industry excels in economic performance, these findings underline the need for significant improvements in both the social and environmental dimensions to achieve balanced and integrated sustainable manufacturing. Addressing these challenges will contribute to the long-term sustainability of the industry, benefiting both its workforce and the environment [54].

Practical and managerial implications

This section highlights key implications of the study for both academia and industry management in the context of sustainable manufacturing. The findings presented here have the potential to significantly enhance the way sustainable manufacturing performance is assessed, particularly within the plywood industry. For academia, this study contributes to a more nuanced understanding of sustainability assessments by incorporating indicators from all three dimensions of the Triple Bottom Line (TBL). While previous research may have applied the TBL framework, this study addresses critical aspects, such as workload and noise levels. By including these factors, this research fills a significant gap and offers a more comprehensive model for evaluating sustainable manufacturing performance. For industry managers and decision-makers, the study's findings provide actionable insights into areas that need attention, particularly within the social and environmental dimensions. By incorporating the indicators used in this research, managers can better assess and improve the sustainability performance of their operations.

From a managerial perspective, several practical actions can be taken to address the low efficiency scores in key indicators and improve sustainability performance within the plywood industry. First, reducing mental workload, which currently has a score of 37.95%, is critical. Managers can achieve this by creating an ergonomic work environment, which would help reduce physical strain and improve comfort for workers. Implementing a work rotation system is another effective strategy to prevent worker fatigue by diversifying tasks and reducing repetitive stress. Additionally, providing training on stress management and coping strategies can help employees handle the pressures of their roles, further reducing mental workload [55].

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Improving safety levels, which currently stand at 24.31%, is also essential. Managers should prioritize regular risk assessments to identify potential hazards in the workplace and implement targeted safety training to equip workers with the knowledge and skills to handle dangerous situations. Enhancing safety infrastructure, such as installing better safety equipment and machinery, can help reduce the likelihood of accidents and improve overall safety levels. Finally, addressing noise levels, which were marked with red indicators across workstations, is crucial for both worker well-being and productivity. Implementing noise-reduction measures such as installing silencers in noisy machinery, providing high-quality ear protection, and redesigning the factory layout to minimize noise exposure are practical steps to mitigate the harmful effects of excessive noise. By taking these actions, plywood industry managers can significantly improve the social and environmental sustainability of their operations, leading to better outcomes for both workers and the organization.

To further enhance efficiency in production time, managers should focus on reducing lead times by optimizing operational procedures, ensuring that each production stage is as efficient as possible. Streamlining processes, eliminating bottlenecks, and implementing automated systems where feasible can significantly reduce time and improve overall productivity. Automation, in particular, can help minimize human errors, increase throughput, and reduce the reliance on manual labor, leading to more consistent and faster production cycles. For improving cost efficiency, a comprehensive analysis should be conducted to identify specific areas of potential savings without compromising product quality. A cost-benefit analysis can be applied to assess where investments in technology, energy efficiency, or raw material usage can yield long-term savings. Adopting a Just-In-Time (JIT) inventory management system can also help reduce waste, minimize excess inventory, and better allocate resources, ensuring that materials are available exactly when needed, without holding unnecessary stock that ties up capital.

In terms of product quality, improving training programs for employees is crucial to ensure they have the necessary skills and knowledge to consistently meet quality standards. Additionally, more stringent quality control measures should be implemented at various production stages, with a focus on identifying defects early in the process. By prioritizing product design improvements and using higher-quality raw materials, manufacturers can also enhance the durability and performance of the final products, thereby meeting customers' increasing expectations for high-quality, sustainable goods. By targeting these interventions and focusing on areas with low efficiency scores, the plywood industry can enhance its operational performance while simultaneously achieving its sustainability goals.

CONCLUSION

This study introduced a comprehensive framework integrating Delphi, BWM, and S-VSM methodologies to evaluate sustainable manufacturing performance. By selecting key indicators through Delphi, assigning weights using BWM, and mapping performance with S-VSM and TLS, the framework provides a structured approach to assessing sustainability. Applied to the plywood industry, it achieved a sustainability score of 80.27% (yellow), signalling moderate efficiency and identifying areas for improvement. The framework demonstrates potential for broader application across industries, enabling targeted enhancements in sustainability, such as optimizing resource utilization and improving energy efficiency. Its versatility makes it a valuable tool for driving sustainable practices in various manufacturing sectors. A notable limitation is its focus on a single production line within one company. Expanding the framework to encompass multiple industries and refining its indicators would provide a more robust assessment, allowing the way for improved sustainability strategies across diverse manufacturing contexts.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest regarding the publication of this manuscript. All research activities and findings were conducted independently and without any external influence or bias.

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APPENDICES

A.1. Formulas for assessing the performance of each indicator

No	Indicators	Notation	Formulas	Sources
1	Time Efficiency	TE = Time Efficiency VAT = Time in Value-Added Activities TT = Total Time NVAT = Time in Non-Value-Added Activities i = index of production process ($i \in n$)	$TE = \frac{VAT}{TT}$ $VAT = \sum_{i=1}^{n}(VATi)$ $NVAT = \sum_{i=1}^{n}(NVATi)$ $TT = VAT + NVAT$	Vinodh, et al. [41]
2	Quality efficiency	QE = Quality Efficiency ND = Number of Defects TM = Total Material s	$QE = 1 - (\frac{ND}{TM})$	Sparks and Badurdeen [42]
3	Inventory efficiency	IE = Inventory Efficiency NI = Total Inventory TM = Total Materials	$IE = \frac{NI}{TM}$	Hartini, et al. [9]
4	Cost Efficiency	CE = Cost Efficiency VAC = Costs in Value-Added Activities NVAC = Cost in Non-Value-Added Activities TC = Total Cost i = index of production process ($i \in n$)	$CE = \frac{VAC}{TC}$ $VAC = \sum_{i=1}^{n}(VACi)$ $NVAC = \sum_{i=1}^{n}(NVACi)$ $TC = VAC + NVAC$	Vinodh, et al. [41]

A.1. Formulas for assessing…. (cont.)

No	Indicators	Notation	Formulas	Sources
5	Material Efficiency	ME = Material Efficiency VAM = Materials in Value-Added Activities TM = Total materials NVAM = Materials in Non-Value Added Activities i = index of production process ($i \in n$)	$\mathrm{ME} = \frac{\mathrm{VAM}}{\mathrm{TM}}$ $\mathrm{VAM} = \sum_{i=1}^{n}(\mathrm{VAMi})$ $\mathrm{NVAM} = \sum_{i=1}^{n}(\mathrm{NVAMi})$ $\mathrm{TM} = \mathrm{VAM} + \mathrm{NVAM}$	Vinodh, et al. [41]
6	Energy Efficiency	EE = Energy Efficiency VAE = Energy in Value-Added Activities NVAE = Energy in Non-Value-Added Activities i = index of production process ($i \in n$)	$\mathrm{EE} = \frac{\mathrm{VAE}}{\mathrm{TE}}$ $\mathrm{VAE} = \sum_{i=1}^{n}(\mathrm{VAEi})$ $\mathrm{NVAM} = \sum_{i=1}^{n}(\mathrm{NVAEi})$ $\mathrm{TE} = \mathrm{VAE} + \mathrm{NVAE}$	Vinodh, et al. [41]
7	Efficiency of Waste Recycle	TW = Total Waste WL = Amount of Land Waste	$WE = 1 - \frac{WL}{TW}$	Helleno, et al. [10]
8	Physical Load Index Efficiency	T2 = score for slight bending (45° forward) T3 = score for very bent (75° forward) T4 = score for entangled T5 = score for sideways hunchback A2 = score for one arm above the shoulder A3 = score for both arms above the shoulder L3 = score for squatting (15° forward) L4 = score for kneeling on one or two feet L5 = score for walking or moving Wu1 = score for lifting/carrying loads perpendicularly (<10kg) Wu2 = score for lifting/carrying perpendicular loads (10-20kg) Wu3 = score for lifting/carrying perpendicular loads (>20kg) Wi1 = score lifting/carrying bending loads (<10kg) Wi2 = score lifting/carrying bending l loads (10-20kg) Wi3 = score for lifting/carrying bending loads (>20kg)	$\mathrm{PLI} = 0.974\mathrm{T}_2 + 1.104\mathrm{T}_3$ $+ 0.068\mathrm{T}_4 + 0.173\mathrm{T}_5$ $+0.157\mathrm{A}_2 + 0.314\mathrm{A}_3$ $+0.405\mathrm{L}_3 + 0.152\mathrm{L}_4$ $+0.152\mathrm{L}_5 + 0.549\mathrm{W}_{u1}$ $+1.098\mathrm{W}_{u2} + 1.647\mathrm{W}_{u3}$ $+1.777\mathrm{W}_{i1} + 2.416\mathrm{W}_{i2}$ $+3.056\mathrm{W}_{i3}$	Hollmann, et al. [43]
9	Mental Load Index Efficiency	RSME Point = Rating scale mental effort	$\text{Mental workload efficiency} = 1 - \left(\frac{\text{RSME Point}}{\text{Highest RSME Point}}\right)$	Hancock and Meshkati [44]
10	Safety Level	NR = Number of work accidents Nac = Total activity	$\mathrm{RE} = 1 - (\frac{\mathrm{NR}}{\mathrm{Nac}})$	Helleno, et al. [10]
11	Noise Level	ND = Noise Dosage MET = Maximum Exposure Time AT = Actual Time	$ND = \frac{AT}{MET} x100\%$ $\text{Noise Level} = 100\% - ND$	Faulkner and Badurdeen [24]

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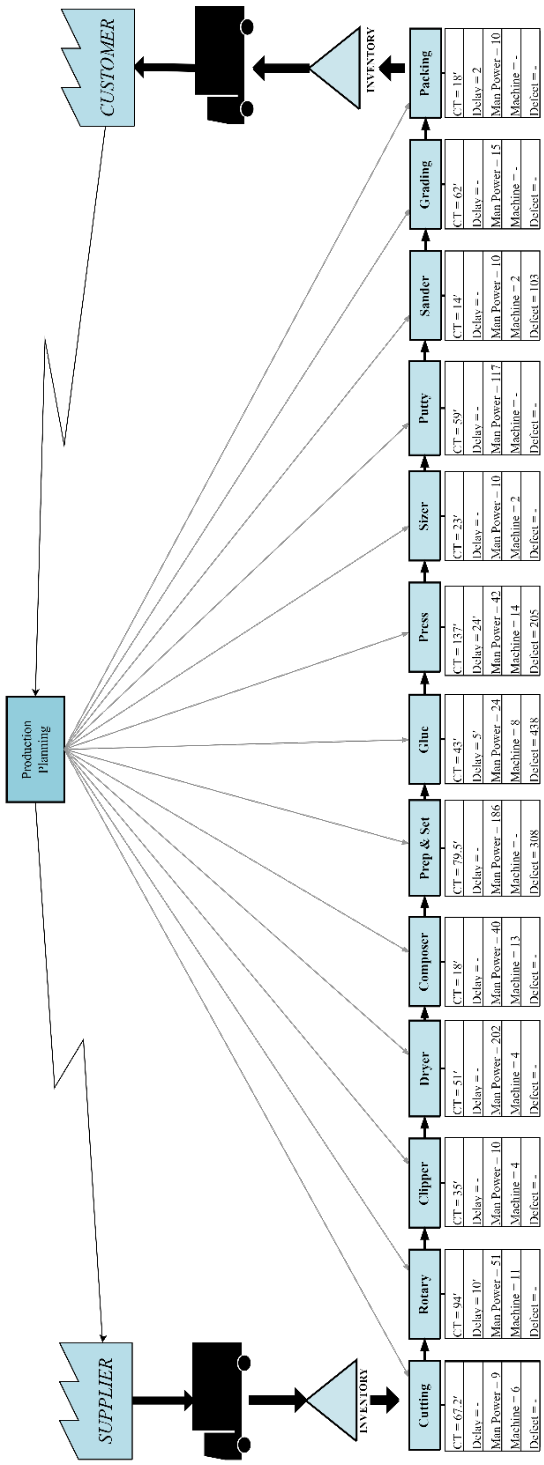
A.2. Mapping results for Sus-VSM in a case study on the plywood Industry



	Cutting	Rotary	Clipper	Dryer	Composer	Prep & Set	Glue	Press	Sizer	Putty	Sander	Grading	Packing	
Time Efficiency	56.85%	71.28%	100.00%	68.63%	66.67%	88.05%	69.77%	76.64%	56.52%	93.22%	71.43%	96.77%	66.67%	**75.58%**
Quality Efficiency	100.00%	100.00%	100.00%	100.00%	100.00%	70.69%	58.33%	80.49%	100.00%	100.00%	90.20%	100.00%	100.00%	**92.29%**
Cost Efficiency	98.06%	85.42%	61.34%	85.19%	87.95%	81.35%	79.24%	92.48%	63.78%	67.41%	67.60%	46.60%	91.12%	**77.50%**
Inventory Efficiency	99.50%	100.00%	100.00%	99.90%	35.10%	100.00%	54.20%	96.50%	100.00%	100.00%	100.00%	100.00%	96.90%	**90.93%**
Material Efficiency	94.99%	95.86%	99.64%	100.18%	99.23%	97.75%	99.10%	95.00%	97.30%	97.74%	98.15%	97.36%	100.00%	**97.87%**
Energy Efficiency	91.67%	91.67%	91.67%	100.00%	100.00%	100.00%	100.00%	100.00%	91.67%	100.00%	91.67%	100.00%	100.00%	**96.79%**
Waste Recycling Efficiency	100.00%	67.06%	97.00%	100.00%	65.00%	99.00%	95.00%	100.00%	90.00%	96.00%	93.33%	99.00%	98.00%	**92.26%**
Physical Load Index Efficiency	97.06%	96.18%	91.77%	92.19%	86.67%	75.69%	90.31%	91.07%	76.39%	67.26%	73.16%	90.80%	86.43%	**85.77%**
Mental Workload Efficiency	40.00%	53.33%	40.00%	26.67%	53.33%	40.00%	20.00%	33.33%	40.00%	26.67%	40.00%	53.33%	26.67%	**37.95%**
Safety Level	33.00%	33.00%	50.00%	100.00%	0.00%	16.67%	33.33%	16.67%	0.00%	0.00%	0.00%	33.00%	0.00%	**24.31%**
Noise Level	68.13%	72.50%	20.00%	82.81%	55.94	93.75%	79.06%	61.25%	25.00%	78.75%	20.00%	94.50%	78.13%	**63.83%**