JOURNAL OF MECHANICS OF CONTINUA AND MATHEMATICAL SCIENCES
www.journalimcms.org

ISSN (Online) : 2454 -7190 Vol.-21, No.-08, August (2026) pp 216-237 ISSN (Print) 0973-8975

WEIGHTING THE SUSTAINABLE MANUFACTURING PRACTICES: A FUZZY ANALYTIC HIERARCHY PROCESS

W. H. W. Mahmood[1,*], R. Tukimin[2], M. Y. Yuhazri[3], A. M. Kamarul[4] A. F. I. Himawan[5]

[1,3,4] Faculty of Industrial and Manufacturing Technology and Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

[2]TVETMARA Kuantan, KM. 8, Jalan Gambang, 25150 Kuantan, Pahang, Malaysia.

[5]School of Economics and Business, Telkom University, Terusan Buahbatu, Bandung 40257, Indonesia.

Email: [1]hasrulnizzam@utem.edu.my, [2]rahayu.tukimin@kuantan.tvetmara.edu.my, [3]yuhazri@utem.edu.my. [4]kamarulamir@utem.edu.my, [5]farislike@telkomuniversity.ac.id

Corresponding Author: **W. H. W. Mahmood**

https://doi.org/10.26782/jmcms.2026.08.00013

(Received: May 14, 2026; Revised: July 28, 2026; Accepted: August 05, 2026)

Abstract

Pressure from customers and stakeholders has forced manufacturing firms to adopt sustainable manufacturing practices into their operations and supply chain management strategies. The three core principles should be considered during their implementation, that consists of economic, environmental, and social. The selection and prioritization of these three core principles become a complex decision-making process. The multi-criteria decision-making techniques can serve as a medium to ease the process of selection and prioritization in a complex system. Thus, this study focuses on prioritizing the sustainable manufacturing practices by determining the weights through Fuzzy Analytic Hierarchy Process in the Malaysian manufacturing sector. The practices were identified through a literature review, questionnaire survey, and consensus obtained from a panel of experts. The findings indicate that environmental was identified as the most important criterion, followed by economic and social. The environmental aspect was emphasized by two: the Environmental Conservation Program and Environmental Recycling and Prevention Program. This finding reveals that the Malaysian manufacturing sector is focusing on 'green factories' since this sector consumes a high percentage of final energy use. In addition, this finding will be beneficial to manufacturing practitioners who intend to transform from conventional to sustainable one. The manufacturing practitioner will *be facilitated to emphasize the important practice and develop a strategy plan to adopt sustainable manufacturing practices.*

Keywords: Sustainable Manufacturing Practice, Malaysian Manufacturing Firm, Multi-Criteria Decision Making, Fuzzy Analytic Hierarchy Process

I. Introduction

The role of the manufacturing sector in contributing to economic development is undeniable. This sector contributed around 30% to gross domestic product (GDP) across the world, and 25% of the world's population is employed in the manufacturing industry [XII]. However, in 2020, the performance of this sector was mostly disrupted due to the widespread coronavirus pandemic, which first exploded in Wuhan, China in December 2019. The world's number of cases is increasing exponentially and has affected many manufacturing units, markets, and other activities of the supply chain [II].

In Malaysia, this virus was detected for the first time in January 2020 with 22 imported cases, and the number of confirmed cases passed 100k by the end of December 2020. Even though the manufacturing sector in Malaysia has been greatly impacted by the pandemic, the operation is still on due to the essentiality of this sector in generating the economy. However, in combating this pandemic, it is essential for this sector to embed sustainability into a long-term recovery and growth plan. This is to allow them to capture opportunities and shape their post-pandemic future for survival. The 'new normal' environment opens an opportunity for sustainable business transition and, at the same time, need to make a supply and production system more resilient [VIII].

The imperative role of sustainable manufacturing practice (SMP) in improving economic, environmental, and social sustainability has been highlighted in various past studies [V], [VI]. It serves as a platform to survive in intense global competition. Recognizing this matter, manufacturers have increasingly begun to promote and implement SMP. Several studies have been conducted on the implementation of SMP among manufacturing firms, particularly in Malaysia. However, most of these tend to focus on specific contexts, such as green practices or social responsibility practices.

Mohd Alias et al. [X] stressed the internal and external factors that motivate the implementation of SMP and the effect of its implementation on sustainability performance. Meanwhile, Abdul-Rashid et al. [XIV] discovered that sustainable manufacturing processes have a significant impact on all elements in sustainability performance, economic, environmental, and social. Thus, it is important for manufacturing to adopt SMP for improving sustainability performance. However, the identification of which practices need to be implemented is crucial [IV], [VII], [IX]. They need to be identified wisely since the degree of impact of SMP on sustainability performance is different in the manufacturing environment [V]. To address this issue, this study focuses on the evaluation of SMP through the judgement of multiple experts in manufacturing. Fuzzy Analytical Hierarchy Process (FAHP) is proposed in determining the priority level of SMP. This approach is chosen as it is much simpler in determining the weight vectors and the consistency in determining human judgements with imprecise and vague information [I], [XI].

II. Result and Discussion

Sustainable Manufacturing Practice

The important key of SMP was extracted through literature review, questionnaire survey, and input from the six chosen industry experts. The FAHP methodology was used to prioritize and rank the finalized and verified SMP.

Empirical Analysis

A literature search yielded a total of 29 Sustainability practice indicators, consisting of nine indicators of economy, 12 indicators of environment, and eight indicators of social. The initial analysis involved mean scores and correlation analysis to assess both the priority and achievement levels of these indicators, providing the basis for the subsequent FAHP analysis.

The survey covered ISO 14001-certified manufacturing firms all over Malaysia, which consisted of 264 companies. Initially, 78 responses were collected. However, after the screening process, 7 responses were eliminated due to inappropriate respondents and incomplete surveys, leaving 71 acceptable responses. Thus, these 71 usable responses were analysed, for analysis that constituted a response rate of 29.55%. The questionnaire was designed to be completed by the person who has working experience for more than 2 years and has knowledge about the issues related to the environment and business aspects, since this study combines these two.

The questionnaire uses two separate five-point rating scales to assess each sustainability indicator: Priority and Current Performance/Achievement as presented in Table 1.

Table 1: Likert scale for questionnaire survey

Score	Priority	Current Performance / Achievement
0	Not Applicable	–
1	Unimportant	Poor
2	Slightly Important	Fair
3	Important	Good
4	Very Important	Very Good
5	Critical	Excellent

The perceived importance of each sustainability practice is reflected in priority. Unimportant (1) or Critical (5) indicates the level of importance for the practice. A score of 0 (Not Applicable) is given where the indicator is irrelevant to the respondent/ organisation.

Current Performance/Achievement is the organisation's current performance for the same sustainability practice. It is rated from 1 (Poor) to 5 (Excellent)

In the case of 'Control the emission of hazardous material,' respondents gauge the importance of the practice and the extent to which it is currently implemented separately. This enables the study to draw comparisons between how important the sustainability practice is and how well it is being achieved, and to identify sustainability practices that are seen as very important but are not performing as well.

Analysis of Economic Practices

The result of the mean score for all EP indicators is presented in Table 2.

Table 2: Mean score of each economic practices indicators for priority and achievement

Item	Economic practices Indicator	Priority	Achievement
EP2	Improve the quality of the product	3.92	3.75
EP3	Increase market share and sales growth	3.85	3.62
EP7	Improve manufacturing capability and flexibility	3.77	3.42
EP8	Reduce non-value-added activities	3.76	3.38
EP4	Quantity of material purchased fit to the planned quantities	3.73	3.72
EP5	All raw materials and parts arrive within the delivery date	3.73	3.63
EP1	Minimize overall operation cost	3.68	3.46
EP6	Reduce total production lead time	3.68	3.44
EP9	Consider the economic effect on the selection of the system	3.58	3.39

Based on the results shown in Table 2, all the EP indicators for the priority have a mean score greater than the achievement. Improve the quality of the product (EP2) has the highest mean score for both priority and achievement, with values of 3.92 and 3.75, respectively. The lowest mean score for priority is to consider the economic effect on the selection of the system (EP9), with a value of 3.58. Meanwhile, for achievement, the lowest is for reducing non-value-added activities (EP8) with a mean value of 3.38. The difference in mean score between priority and achievement is shown in Figure 1. The result indicates that reducing non-value-added activities (EP8) has the highest gap in mean score, with a value of 0.38, and the quantity of material purchased fit to the planned quantities (EP4) has the lowest gap in mean score, with a value of 0.01. The significant gap of EP8 needs to be taken into account due to the relation of EP8 with the cost.

Fig. 1. The difference of mean scores between the level of priority and achievement for the economic performance indicators

Correlation Analysis of Economic Practices

Table 3 and Table 4 show the results of correlation analysis for economic performance for the level of priority and achievement, respectively. A total of 36 matrices were produced for each level, which were significant at a level of 0.01. For the level of priority, all matrices show a positive correlation, with 5 pairs (13.9%) for very strong, 28 pairs (77.8%) for strong, and 3 pairs (8.3%) for moderate correlation. The correlation coefficients are in the range of 0.551 to 0.858. The highest correlation coefficient appears between improving the quality of the product (EP2) and increasing market share and sales growth (EP3). This result suggests that market share and sales growth can be strengthened by improving the quality of products. However, the impact of quality on market share and sales growth is not sufficient without innovativeness. Hence, quality and innovativeness should be balanced to create high market share and sales growth.

Another strong linkage appears between improved manufacturing capability and flexibility (EP7) and reduced non-value-added activities (EP8). Hence, the application of lean management is suitable to reduce this waste. A high correlation coefficient also exist for another three pairs; between all raw materials and parts arrive within the delivery date (EP5) and improve manufacturing capability and flexibility (EP7), all raw materials and parts arrive within the delivery date (EP5) and reduce total production lead time (EP6), and increase market share and sales growth (EP3) and reduce the non-value-added activities (EP8).

Table 3. Spearman rank order correlation for economic practices (priority)

	EP1	EP2	EP3	EP4	EP5	EP6	EP7	EP8
EP2	0.647							
EP3	0.737	0.858						
EP4	0.757	0.766	0.776					
EP5	0.666	0.785	0.768	0.731				
EP6	0.775	0.685	0.773	0.748	0.812			
EP7	0.642	0.778	0.788	0.760	0.835	0.738		
EP8	0.745	0.686	0.806	0.675	0.748	0.777	0.813	
EP9	0.624	0.551	0.646	0.578	0.594	0.603	0.664	0.770

Correlation is significant at the 0.01 level (2-tailed)

Correlation strength:

0.400 – 0.599 Moderate, 0.600 – 0.799 Strong, 0.800 – 1.000 Very strong

Table 4: Spearman rank order correlation for economic practices (achievement)

	EP1	EP2	EP3	EP4	EP5	EP6	EP7	EP8
EP2	0.505							
EP3	0.567	0.653						
EP4	0.440	0.569	0.513					
EP5	0.429	0.609	0.512	0.752				
EP6	0.610	0.565	0.574	0.738	0.779			
EP7	0.530	0.586	0.545	0.764	0.736	0.795		
EP8	0.531	0.583	0.396	0.519	0.677	0.676	0.739	
EP9	0.555	0.673	0.656	0.638	0.651	0.682	0.700	0.685

In terms of achievement level, all 36 matrices produced show a significant positive correlation. 28 pairs (77.8%) show a significantly strong correlation, with the correlation coefficient ranging from 0.609 to 0.795. 16 pairs (44.4%) show a significant positive moderate correlation, and 1 pair (2.8%) shows a significant positive weak correlation. In the meantime, the result shows that the highest correlation coefficient exists between EP6 and EP7, 0.779. This result suggests that there is a close linkage between manufacturing capability and flexibility with a reduction of total production lead time.

Analysis of Environmental Performance

The mean score for EvP is calculated, and the result is tabulated in Table 5. There are differences between the mean score for the level of priority and achievement. For the priority, the highest score is to improve compliance with environmental law (EvP7) with a mean score of 3.69, and the lowest is for reducing energy and fuel consumption (EvP6) with a mean score of 3.31. For the level of achievement, the highest mean score is for controlling the emission of hazardous material (EvP1) with a mean score of 3.54, whereas the lowest mean score is for using eco-friendly material in product and manufacturing process (EvP9) and reducing energy and fuel consumption (EvP6), with a similar mean score of 3.18. The difference in mean score between priority and achievement is calculated and arranged in descending order as presented in Figure 2. The indicator with the highest gap is the reduction of the consumption of toxic material (EvP2) with a value of 0.28, and the lowest gap is the emission of hazardous material (EvP1) with a value of 0.08.

Table 5: Mean score of each environmental practices indicator for both level of priority and achievement

Item	Environmental performance	Priority	Achievement
EvP7	Improve compliance with environmental law	3.69	3.45
EvP3	Reduction of hazardous waste	3.65	3.39
EvP1	Control the emission of hazardous material	3.62	3.54
EvP11	Develop waste reduction and energy efficiency programs	3.58	3.34
EvP12	Consider the direct environmental effect on the operation	3.55	3.44

EvP2	Reduce the consumption of toxic material	3.55	3.27
EvP4	Increase the usage of recycled waste material and products	3.48	3.30
EvP8	Increase the use of renewable material in product and process	3.41	3.20
EvP9	Use eco-friendly material in the product and manufacturing process	3.37	3.18
EvP10	Consider using easily degradable chemicals in the product and production process	3.37	3.20
EvP5	Increase the usage of recycling product	3.32	3.20
EvP6	Reduce the consumption of energy and fuel	3.31	3.18

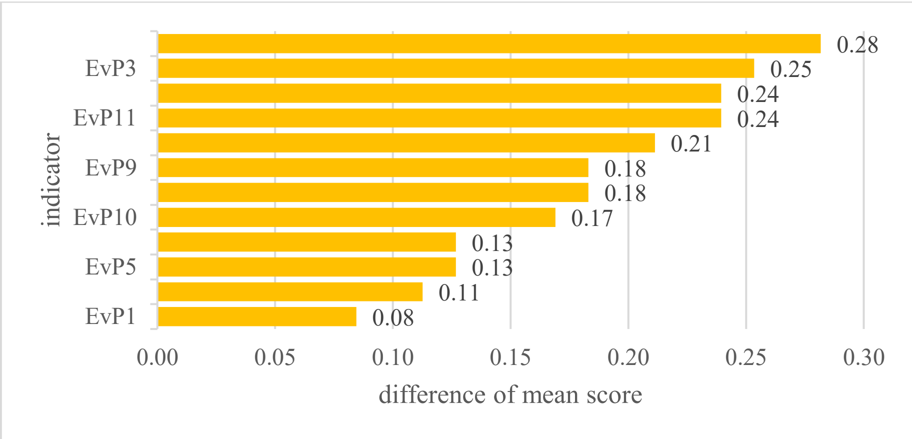

Fig. 2. The difference in mean score between the level of priority and achievement for environmental practices indicators

Correlation for Environmental Practices

Correlation analysis among 12 EvP indicators generates a total of 66 matrices, which show a positive correlation relationship for both levels of priority and achievement and prove significant at level 0.01. The results are given in Table 6 and Table 7, respectively.

Table 6: Spearman rank order correlation for environmental practices (priority)

	EvP1	EvP2	EvP3	EvP4	EvP5	EvP6	EvP7	EvP8	EvP9	EvP10	EvP11
EvP2	0.756										
EvP3	0.882	0.873									
EvP4	0.567	0.709	0.698								
EvP5	0.665	0.750	0.737	0.849							
EvP6	0.483	0.488	0.501	0.604	0.601						
EvP7	0.727	0.682	0.753	0.606	0.603	0.458					
EvP8	0.573	0.634	0.654	0.616	0.681	0.640	0.571				
EvP9	0.644	0.639	0.614	0.537	0.751	0.572	0.597	0.784			
EvP10	0.551	0.608	0.610	0.563	0.647	0.621	0.524	0.754	0.780		
EvP11	0.707	0.519	0.666	0.490	0.519	0.511	0.763	0.695	0.731	0.696	
EvP12	0.742	0.585	0.710	0.516	0.592	0.527	0.706	0.640	0.693	0.668	0.823

Correlation is significant at the 0.01 level (2-tailed)
Correlation strength:

0.400 – 0.599 Moderate, 0.600 – 0.799 Strong, 0.800 – 1.000 Very strong

For the level of priority, the correlation coefficients are in the range of 0.458 to 0.882. 4 pairs (6.1%) show a very strong positive correlation, 41 pairs (62.1%) show a strong positive correlation ranging in value from 0.601 to 0.784, and another 21 pairs (31.8%) show a strong positive correlation ranging in value from 0.458 to 0.597. However, for the level of achievement, the correlation coefficient ranged from 0.260 to 0.814. Only 1 pair (1.5%) shows a very strong positive correlation with the correlation coefficient 0.814. 28 pairs (42.4%) show a strong positive correlation ranging in value from 0.600 to 0.719, 25 pairs (37.9%) show positive moderate correlation ranging in value from 0.441 to 0.598, and the other 12 pairs (18.2%) show positive weak correlation ranging in value from 0.260 to 0.380.

Table 7: Spearman rank order correlation for environmental practices (achievement)

	EvP1	EvP2	EvP3	EvP4	EvP5	EvP6	EvP7	EvP8	EvP9	EvP10	EvP11
EvP2	0.669										
EvP3	0.644	0.750									
EvP4	0.372	0.564	0.637								
EvP5	0.484	0.598	0.752	0.814							
EvP6	0.361	0.318	0.567	0.480	0.594						
EvP7	0.522	0.550	0.659	0.467	0.441	0.380					
EvP8	0.373	0.460	0.646	0.629	0.720	0.788	0.354				
EvP9	0.510	0.496	0.600	0.533	0.701	0.642	0.471	0.697			
EvP10	0.372	0.359	0.562	0.534	0.682	0.710	0.323	0.685	0.775		
EvP11	0.575	0.329	0.469	0.260	0.368	0.558	0.647	0.444	0.644	0.460	
EvP12	0.716	0.588	0.754	0.486	0.644	0.661	0.578	0.690	0.794	0.663	0.698

Correlation is significant at the 0.01 level (2-tailed)
Correlation strength:

0.200 – 0.399 Weak, 0.400 – 0.599 Moderate, 0.600 – 0.799 Strong, 0.900 – 1.000 Very strong

Analysis of social practices

As presented in Table 8, employee safety and health (SP1) become the most important indicator for both priority and achievement with a value of the mean score is 3.83 and 3.65, respectively. The difference in mean score between the level of priority and achievement is calculated to observe the gap between the two levels. The result is given in Figure 3. Based on this result, the indicator that has the biggest gap has improved the relationship with communities and stakeholders (SP3), with a value of 0.25, and the lowest gap complies with the environmental and safety regulation (SP6), with a value of 0.05. The result also indicates that all indicators for the level of priority are greater than achievement.

Table 8: Mean score of each social practices indicator for both the level of priority and achievement

Item	Social performance indicator	Priority	Achievement
SP1	Improve employee safety and health	3.83	3.65
SP6	Comply with environmental and safety regulations	3.75	3.70
SP2	Improve work environment	3.69	3.48
SP8	Develop a standard process to establish consistency across the organisation	3.63	3.51
SP4	Consider the current technology feasibility and labour safety in operation	3.63	3.49
SP3	Improve relationship with communities and stakeholders	3.56	3.31
SP7	Consider the direct social effect and community in product development	3.56	3.45
SP5	Collaborate with stakeholders regarding environmental issues	3.52	3.44

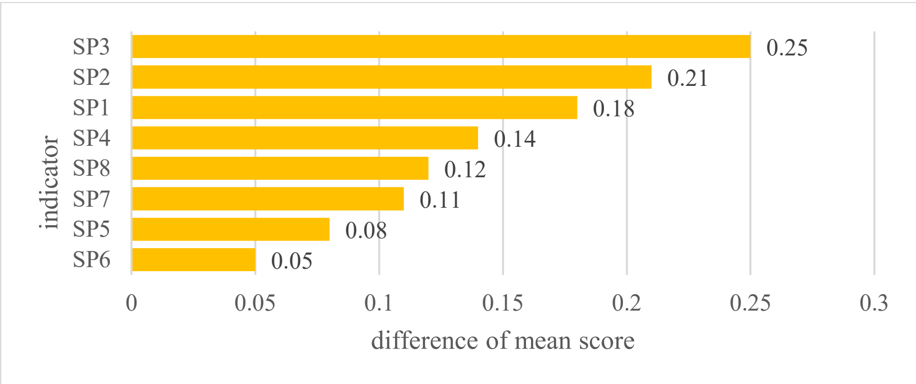

Fig. 3. The difference in mean score between the level of priority and achievement for social performance indicators

Correlation Analysis for Social Practices

A total of 28 matrices of the relationship among 8 social performance indicators were generated for both levels: priority and achievement, and the results are shown in Table 9 and Table 10, respectively. The analysis results for priority show that the correlation coefficient ranged from 0.710 to 0.874, indicating a positive correlation and proving significant at the 0.01 level. 6 pairs (21.4%) show a very strong positive correlation, and the other 22 pairs (78.6%) show a strong positive correlation.

Table 9: Spearman rank order correlation matrix of social practice indicators (priority)

	SP1	SP2	SP3	SP4	SP5	SP6	SP7
SP2	0.874						
SP3	0.820	0.867					

SP4	0.791	0.781	0.718				
SP5	0.796	0.743	0.748	0.790			
SP6	0.752	0.728	0.710	0.845	0.752		
SP7	0.748	0.764	0.774	0.758	0.806	0.670	
SP8	0.746	0.753	0.780	0.856	0.720	0.779	0.792

Correlation is significant at the 0.01 level (2-tailed)

Meanwhile, for the level of achievement, all pairs show a positive correlation, where 2 pairs (7.1%) are found to have a very strong correlation, 21 pairs (75.0%) show a strong correlation, and the remaining 5 pairs (17.9%) show a moderate correlation.

Table 10: Spearman Rank Order Correlation Matrix of Social practices (Achievement)

	SP1	SP2	SP3	SP4	SP5	SP6	SP7
SP2	0.701						
SP3	0.754	0.801					
SP4	0.644	0.531	0.575				
SP5	0.660	0.639	0.711	0.670			
SP6	0.618	0.597	0.562	0.691	0.681		
SP7	0.660	0.775	0.766	0.756	0.732	0.655	
SP8	0.569	0.728	0.684	0.731	0.698	0.722	0.875

Correlation is significant at the 0.01 level (2-tailed)

Fuzzy Analytic Hierarchy Process

FAHP is a popular multicriteria decision-making method (MCDM) tool due to its ability to consider uncertainty and vagueness that exist in the problem. It is also a subjective tool that is commonly used in weight determination. The FAHP methodology is summarized and visualized in Figure 4, which consists of ten steps.

The process begins with translating the entire problem into a hierarchical level that includes the objective, the criteria, the sub-criteria, and the alternatives. The decision maker makes judgements in terms of pairwise comparisons at each level using verbal judgements, which will be translated into numbers as presented in Table 11.

Table 11: Preference Value Scale

Preference Value	Numeric Value	TFN (b^-, b, b^+)	Reciprocal TFN
Equally important	1	(1,1,2)	(1/2, 1, 1)
Equally to moderately important	2	(1,2,3)	(1/3, 1/2, 1)
Moderately important	3	(2,3,4)	(1/4, 1/3, 1/2)
Moderately to strongly important	4	(3,4,5)	(1/5, 1/4, 1/3)
Strongly important	5	(4,5,6)	(1/6, 1/5, 1/4)
Strongly to very strongly important	6	(5,6,7)	(1/7, 1/6, 1/5)
Very strong importance	7	(6,7,8)	(1/8, 1/7, 1/6)
Very strongly to extremely important	8	(7,8,9)	(1/9, 1/8, 1/7)
Extremely important	9	(8,9,9)	(1/8, 1/9, 1/9)

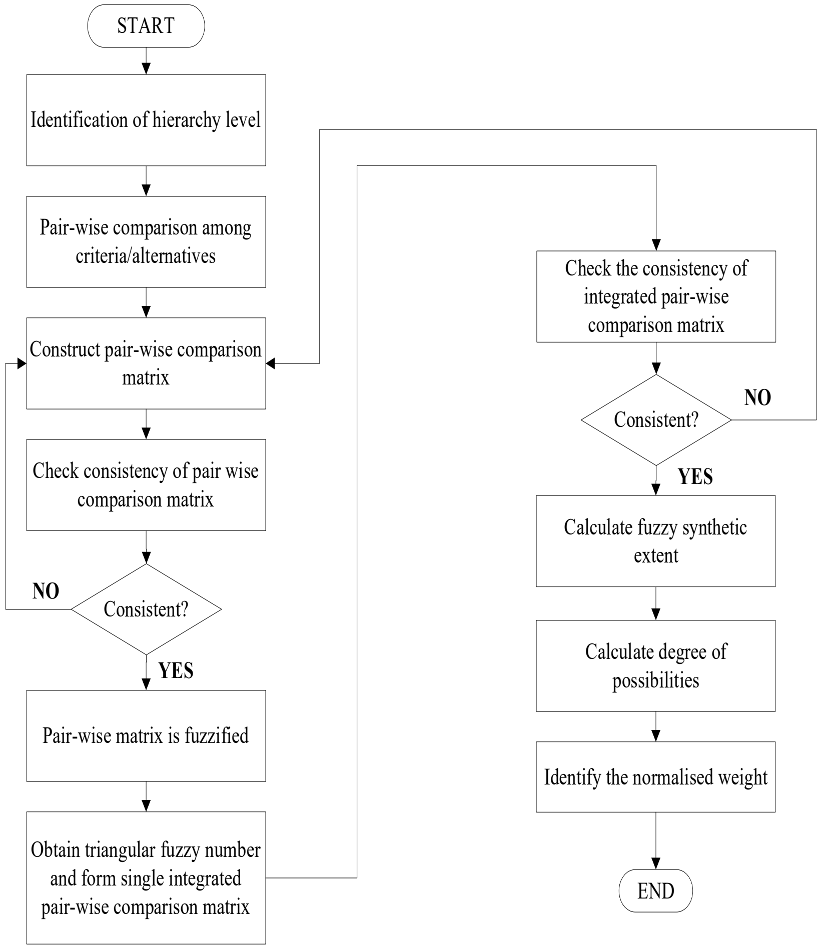

Fig. 4. FAHP methodology

The pairwise comparison made is transformed into matrix form to determine the consistency of the judgement as follows:

$$\widetilde{A}=\begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & 1 & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & 1 \end{bmatrix} \tag{1}$$

where $a_{ij}=\left(b_{ij}^{-}, b_{ij}, b_{ij}^{+}\right)$ and $a_{ji}=\frac{1}{a_{ij}}$

The consistency level is determined by calculating the consistency index (CI) and consistency ratio (CR) using equations (2) and (3).

$$CI=\frac{(\lambda_{max}-n)}{(n-1)} \tag{2}$$

and

$$CR=\frac{CI}{RI} \tag{3}$$

where

λ_{max} = maximum eigenvalue

n = size of matrix

RI = random consistency index as Table 12.

Table 12: Random consistency index

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The calculated consistency ratio must be less than 10%. If the value is greater than 10%, decision makers must revise the pairwise comparison and recalculate the consistency ratio. Once the judgements meet the accepted level of consistency, the process continues to the extent analysis where the pairwise comparison matrix is fuzzified. The triangular fuzzy number (TFN) used in the transformation process is expressed as (b-, b, b+) to define fuzziness. The value of b- is the smallest possible value, b is the most likely value, and b+ is the largest possible value. The geometric mean method (4) is used to aggregate the pairwise comparison matrix.

$$\begin{aligned} b_{ij}^{-}&=\left[\prod_{k=1}^{s} P_{ijk}\right]^{\left(\frac{1}{k}\right)} \quad \text{where } k=1, 2, \dots\dots, s \\ b_{ij}&=\left[\prod_{k=1}^{s} Q_{ijk}\right]^{\left(\frac{1}{k}\right)} \quad \text{where } k=1, 2, \dots\dots, s \\ b_{ij}^{+}&=\left[\prod_{k=1}^{s} R_{ijk}\right]^{\left(\frac{1}{k}\right)} \quad \text{where } k=1, 2, \dots\dots, s \end{aligned} \tag{4}$$

The fuzzy judgment matrix is defuzzified as (5) to check the consistency of aggregated pairwise comparison.

$$\bar{b}_{ij}=\frac{\left(b_{ij}^{-}+4b_{ij}+b_{ij}^{+}\right)}{6} \tag{5}$$

The process of pairwise comparisons by decision makers needs to be revised if the consistency level is not met. The fuzzy synthetic extent, S_i is then calculated using (5).

$$S_i=\sum_{j=1}^{m}\bar{b}_{ij}\otimes\left[\sum_{i=1}^{n}\sum_{j=1}^{m}\bar{b}_{ij}\right]^{-1} \tag{6}$$

where

$$\sum_{j=1}^{m}\bar{b}_{ij}=\left(\sum_{j=1}^{m}b_j^{-},\sum_{j=1}^{m}b_j,\sum_{j=1}^{m}b_j^{+}\right)$$

and

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\bar{b}_{ij}=\left(\sum_{i=1}^{n}b_i^{-},\sum_{i=1}^{n}b_i,\sum_{i=1}^{n}b_i^{+}\right)$$

The non-fuzzy synthetic value that represents the relative preference of one criterion over others is calculated using Chang's method to find the degree of possibility.

$$(S_2\geq S_1)=\begin{cases} 1 & \text{, if } b_2\geq b_1 \\ 0 & \text{, if } b_1^{-}\geq b_2^{+} \\ \dfrac{b_1^{-}-b_2^{+}}{\left(b_2-b_2^{+}\right)-\left(b_1-b_1^{-}\right)} & \text{, otherwise} \end{cases} \tag{7}$$

The minimum value between the degree of possibilities is the weight obtained for the respective criteria. However, this weighting is normalised to determine the priority for each criterion. The ranking is determined according to the normalised weight.

III. Results and Discussion

The hierarchy level of SMP is shown in Figure 5. It consists of four levels: the objective, the criteria, the sub-criteria, and the alternatives. This hierarchy is important to prevent misinterpretation and achieve the main objective. Six experts, denoted as experts A, B, C, D, E, and F, from industry with at least 10 years' experience involved in the process of judgement for pairwise comparison for each level of the hierarchy. The pairwise comparison made by these experts is then translated into the form of a matrix. If the criterion/alternative *i* dominates over criterion/alternative *j*, the scale given by the experts is entered in row *i* and column *j*. The reciprocal is then entered in row j and column *i*.

There are six pairwise comparison matrices for each level of hierarchy since the number of experts involved is six. The pairwise comparison matrix by expert A for the first level of hierarchy is given in Table 13, with an acceptable consistency level (less than 10%). The matrix is then fuzzified using TFN and given in Table 14.

Table 13: Pairwise comparison matrix by expert A

	C1	C2	C3
C1	1	$\frac{1}{3}$	1
C2	3	1	3
C3	$\frac{1}{1}$	$\frac{1}{3}$	1

Table 14: Fuzzified pairwise comparison matrix by expert A

	C1	C2	C3
C1	1,1,2	$\frac{1}{4},\frac{1}{3},\frac{1}{2}$	1,1,2
C2	2,3,4	1,1,2	2,3,4
C3	$\frac{1}{2},\frac{1}{1},\frac{1}{1}$	$\frac{1}{4},\frac{1}{3},\frac{1}{2}$	1,1,2

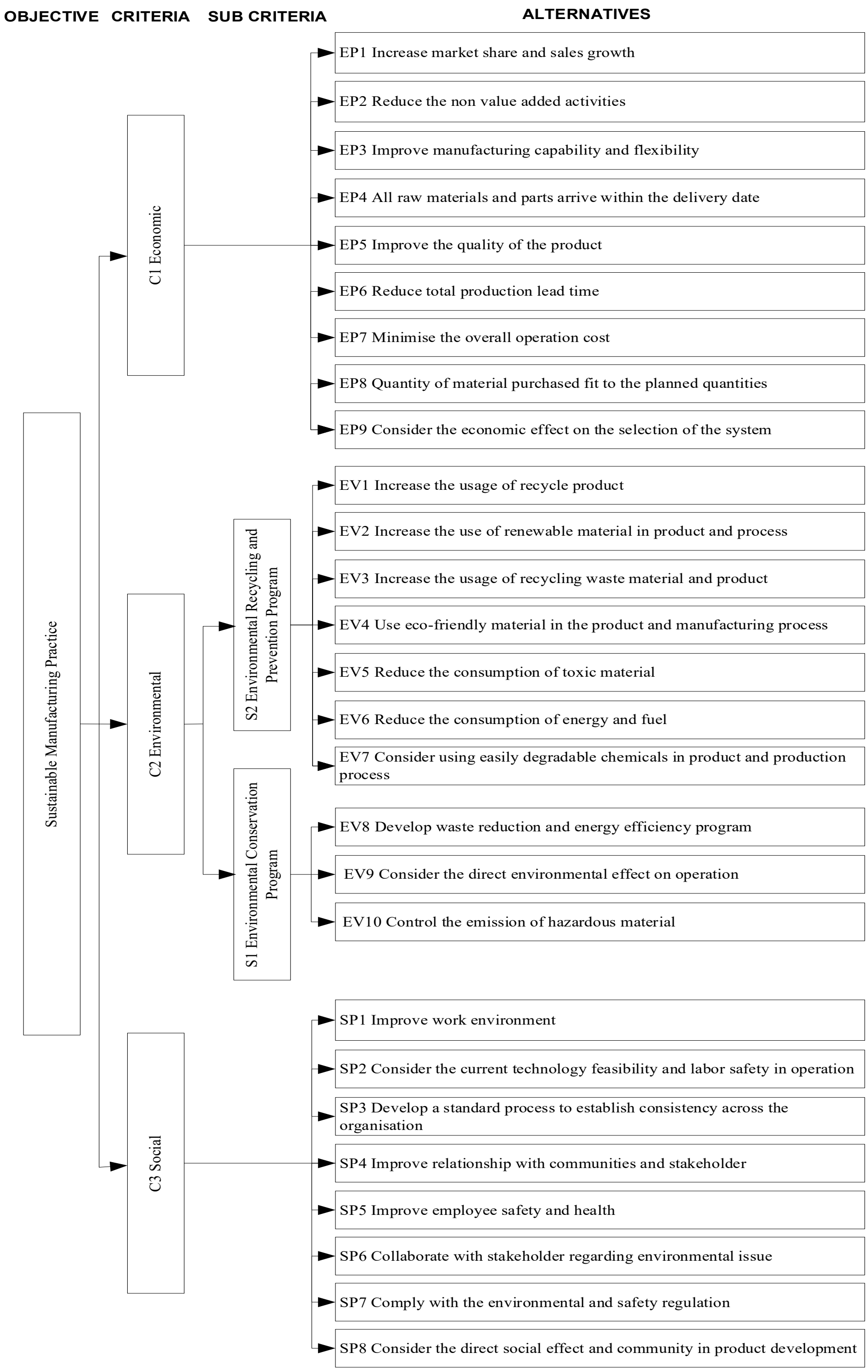

Fig. 5. Hierarchy of Sustainable Manufacturing Practice

The aggregated fuzzified pairwise comparison matrix by six experts was then determined using the geometric mean method to combine all six fuzzified pairwise comparison matrices. The result is presented in Table 15.

Table 15: Aggregated fuzzified pairwise comparison matrix

	C1	C2	C3
C1	1.00, 1.00, 2.00	0.63, 0.69, 1.26	1.12, 1.20, 2.24
C2	0.79, 1.44, 1.59	1.00, 1.00, 2.00	1.41, 1.73, 2.83
C3	0.45, 0.83, 0.89	0.35, 0.58, 0.71	1.00, 1.00, 2.00

The aggregated pairwise comparison matrix is then defuzzified using (4) to determine the consistency level. The defuzzified aggregated pairwise comparison matrix is shown in Table 16.

Table 16: Defuzzified aggregated pairwise comparison matrix

	C1	C2	C3
C1	1.17	0.78	1.36
C2	1.36	1.17	1.86
C3	0.78	0.56	1.17

Once the consistency level is met, the fuzzy synthetic extent value is determined as (5). The result shown in Table 17.

Table 17: Fuzzy Synthetic Extent Value

	Fuzzy Synthetic Extent Value
C1	(0.177, 0.305, 0.709)
C2	(0.207, 0.440, 0.827)
C3	(0.116, 0.254, 0.464)

The non-fuzzy synthetic value that represents the relative preference of one criterion over others is calculated to find the degree possibility using equation (6) as follows:

For C1;

$V(S_{C1} \geq S_{C2}) = (0.207\text{-}0.709)/[(0.305\text{-}0.709)\text{-}(0.440\text{-}0.207)] = 0.788$

$V(S_{C1} \geq S_{C3}) = 1.00$

Hence, the relative preference of C1 is

$V\left(S_{C1} \geq S_{C2}, S_{C3}\right) = \min(0.788, 1.00)$

$= 0.788$

For C2;

$V(S_{C2} \geq S_{C1}) = 1.00$

$V(S_{C2} \geq S_{C3}) = 1.00$

Hence, the relative preference of C2 is

$V\left(S_{C2} \geq S_{C1}, S_{C3}\right) = \min(1.00, 1.00)$

$= 1.00$

For C3;

$V(S_{C3} \geq S_{C1}) = (0.177\text{-}0.464)/[(0.254\text{-}0.464)\text{-}(0.305\text{-}0.177)]$

$= 0.849$

$V(S_{C8} \geq S_{C7}) = (0.207\text{-}0.464)/[(0.254\text{-}0.464)\text{-}(0.440\text{-}0.207)]$

$= 0.580$

Hence, the relative preference of C3 is

$V\left(S_{C3} \geq S_{C1}, S_{C2}\right) = \min(0.849, 0.580)$

$= 0.580$

Finally, the weight is normalized to determine the priority for each criterion. The final priority for each criterion is presented in Table 18.

Table 18: The normalized weight for each criterion in the first level of hierarchy

	Relative weight (w'(*Si*))	Normalized weight (w(*Si*))
C1	0.788	0.333
C2	1.000	0.422
C3	0.580	0.245
Total	2.368	

The same process is repeated for the level of sub-criteria and alternative. Table 19 shows the fuzzified pairwise comparison matrix for sub-criteria and alternatives under C1, C2, and C3. Figure 6 shows the priority level for each of the criteria, sub-criteria, and alternatives that are arranged based on their normalized weight. The results show that all of them have relatively healthy weights. Thus, it can be concluded that all of them are important. However, the degree of impact is different as they have different weights.

According to the FAHP methodology, the environmental criterion was ranked the most important, followed by the economic and Social criterion. The findings were driven by the necessity of environmental responsibility caused by continual pressure that many organizations face with regard to the development of environmentally friendly products and the use of less harmful operations. This result found that the SMP in terms of environmental practices does improve the firm's performance not only in environmental performance, but also in product quality, which in turn improves the economic performance. This finding is also consistent with a study done in Ghana that found environmental sustainability practices do have significant profit margins in the operational activities [IV]. Besides, environmental practices also play a crucial role in reaching higher sustainable performance as they directly improve economic and social performance [VII], [XV].

The second highest criterion is economic with a weight of 0.333. This criterion was undoubtedly important as it is an assessment of a firm's success in the field related to liabilities, assets, and overall market strength. It is also associated with the maximization of financial benefits for internal and external stakeholders.

Table 19: Aggregated Fuzzified Pairwise Comparison Matrix

Aggregated fuzzified pairwise comparison matrix

Sub criteria

$$\begin{bmatrix} 1.00,1.00,2.00 & 0.79,0.83,1.59 \\ 0.63,1.20,1.26 & 1.00,1.00,2.00 \end{bmatrix}$$

Alternatives C1

$$\begin{bmatrix} 1.00,1.00,2.00 & 1.12,1.20,2.24 & 1.26,1.44,2.52 & 1.41,1.73,2.83 & 0.79,0.83,1.59 & 1.26,1.44,2.52 & 1.12,1.20,2.24 & 1.26,1.44,2.52 & 1.26,1.31,2.40 \\ 0.45,0.83,0.89 & 1.00,1.00,2.00 & 1.12,1.20,2.24 & 1.26,1.44,2.52 & 0.63,0.69,1.26 & 1.12,1.20,2.24 & 1.00,1.00,2.00 & 1.12,1.20,2.24 & 1.12,1.20,2.24 \\ 0.40,0.69,0.79 & 0.45,0.83,0.89 & 1.00,1.00,2.00 & 1.12,1.20,2.24 & 0.59,0.64,1.12 & 0.89,1.00,1.78 & 0.79,0.83,1.59 & 1.00,1.00,2.00 & 0.89,1.00,1.78 \\ 0.35,0.57,0.71 & 0.40,0.69,0.79 & 0.45,0.83,0.89 & 1.00,1.00,2.00 & 0.47,0.53,0.89 & 0.79,0.83,1.59 & 0.63,0.69,1.26 & 0.79,0.83,1.59 & 0.71,0.83,1.41 \\ 0.63,1.20,1.26 & 0.56,1.00,1.12 & 0.63,1.20,1.26 & 1.12,1.89,2.14 & 1.00,1.00,2.00 & 1.41,1.73,2.83 & 1.26,1.44,2.52 & 1.41,1.57,2.70 & 1.41,1.57,2.70 \\ 0.40,0.69,0.79 & 0.45,0.83,0.89 & 0.56,1.00,1.12 & 0.63,1.20,1.26 & 0.35,0.57,0.71 & 1.00,1.00,2.00 & 0.79,0.83,1.59 & 0.89,1.00,1.78 & 0.89,1.00,1.78 \\ 0.45,0.83,0.89 & 0.50,1.00,1.00 & 0.63,1.20,1.26 & 0.79,1.44,1.59 & 0.40,0.69,0.79 & 0.63,1.20,1.26 & 1.00,1.00,2.00 & 1.12,1.20,2.24 & 1.12,1.20,2.24 \\ 0.40,0.69,0.79 & 0.45,0.83,0.89 & 0.50,1.00,1.00 & 0.63,1.20,1.26 & 0.37,0.64,0.71 & 0.56,1.00,1.12 & 0.45,0.83,0.89 & 1.00,1.00,2.00 & 0.89,1.00,1.78 \\ 0.42,0.76,0.79 & 0.45,0.83,0.89 & 0.56,1.00,1.12 & 0.71,1.20,1.41 & 0.37,0.64,0.71 & 0.56,1.00,1.12 & 0.45,0.83,0.89 & 0.56,1.00,1.12 & 1.00,1.00,2.00 \end{bmatrix}$$

Alternatives S1

$$\begin{bmatrix} 1.00,1.00,2.00 & 0.79,0.83,1.59 & 0.63,0.69,1.26 & 0.71,0.83,1.41 & 0.63,0.69,1.26 & 1.51,1.81,2.70 & 0.85,0.96,1.59 \\ 0.63,1.20,1.26 & 1.00,1.00,2.00 & 0.71,0.83,1.41 & 0.89,1.00,1.78 & 0.71,0.83,1.41 & 1.91,2.17,3.40 & 1.07,1.15,2.00 \\ 0.56,1.00,1.12 & 0.50,0.83,1.00 & 1.00,1.00,2.00 & 0.74,0.83,1.35 & 0.74,0.76,1.41 & 1.35,1.63,2.29 & 0.95,1.15,1.78 \\ 0.71,1.20,1.41 & 0.56,1.00,1.12 & 0.74,1.20,1.35 & 1.00,1.00,2.00 & 0.84,0.92,1.59 & 1.91,2.17,3.40 & 1.07,1.00.15,2 \\ 0.79,1.44,1.59 & 0.71,1.20,1.41 & 0.71,1.31,1.35 & 0.63,1.09,1.20 & 1.00,1.00,2.00 & 1.91,2.36,3.24 & 1.20,1.38,2.24 \\ 0.37,0.55,0.66 & 0.30,0.46,0.53 & 0.44,0.61,0.74 & 0.30,0.46,0.53 & 0.31,0.42,0.53 & 1.00,1.00,2.00 & 0.60,0.69,1.05 \\ 0.63,1.04,1.18 & 0.50,0.87,0.94 & 0.63,0.94,1.13 & 0.50,0.87,0.94 & 0.45,0.72,0.84 & 1.00,1.53,1.78 & 1.00,1.00,2.00 \end{bmatrix}$$

Alternatives S2

$$\begin{bmatrix} 1.00,1.00,2.00 & 0.79,0.83,1.59 & 0.89,1.00,1.78 \\ 0.63,1.20,1.26 & 1.00,1.00,2.00 & 1.12,1.20,2.24 \\ 0.56,1.00,1.12 & 0.45,0.83,0.89 & 1.00,1.00,2.00 \end{bmatrix}$$

Alternatives C3

$$\begin{bmatrix} 1.00,1.00,2.00 & 0.63,0.69,1.26 & 0.63,0.69,1.26 & 1.00,1.00,2.00 & 0.63,0.69,1.26 & 1.00,1.00,2.00 & 0.55,0.58,1.00 & 1.00,1.09,1.91 \\ 0.79,1.44,1.59 & 1.00,1.00,2.00 & 1.00,1.00,2.00 & 1.26,1.44,2.52 & 0.89,1.00,1.78 & 1.26,1.44,2.52 & 0.63,0.69,1.26 & 1.35,1.38,2.52 \\ 0.79,1.44,1.59 & 0.50,1.00,1.00 & 1.00,1.00,2.00 & 1.26,1.44,2.52 & 0.89,1.00,1.78 & 1.26,1.44,2.52 & 0.63,0.69,1.26 & 1.35,1.38,2.52 \\ 0.50,1.00,1.00 & 0.40,0.69,0.79 & 0.40,0.69,0.79 & 1.00,1.00,2.00 & 0.63,0.69,1.26 & 1.00,1.00,2.00 & 0.55,0.58,1.00 & 1.00,1.09,1.91 \\ 0.79,1.44,1.59 & 0.56,1.00,1.12 & 0.56,1.00,1.12 & 0.79,1.44,1.59 & 1.00,1.00,2.00 & 1.26,1.44,2.52 & 0.66,0.76,1.26 & 1.20,1.38,2.24 \\ 0.50,1.00,1.00 & 0.40,0.69,0.79 & 0.40,0.69,0.79 & 0.50,1.00,1.00 & 0.40,0.69,0.79 & 1.00,1.00,2.00 & 0.55,0.58,1.00 & 1.00,1.09,1.91 \\ 1.00,1.71,1.82 & 0.79,1.44,1.59 & 0.79,1.44,1.59 & 1.00,1.71,1.82 & 0.79,1.31,1.51 & 1.00,1.71,1.82 & 1.00,1.00,2.00 & 1.59,1.73,2.88 \\ 0.53,0.92,1.00 & 0.40,0.72,0.74 & 0.40,0.72,0.74 & 0.53,0.92,1.00 & 0.45,0.72,0.84 & 0.53,0.92,1.00 & 0.35,0.58,0.63 & 1.00,1.00,2.00 \end{bmatrix}$$

LESS IMPORTANT

C2 Environmental (0.422)		**C1 Economic (0.333)**	**C3 Social (0.245)**
S2 Environmental Conservation Program (0.527)	**S1** Environmental Recycling and Prevention Program (0.473)	**EP 5** Improve the quality of product (0.049)	**SP7** Comply with the environmental and safety regulation (0.042)
EV9 Consider the direct environmental effect on operation (0.154)	**EV5** Reduce the consumption of toxic material (0.037)	**EP1** Increase market share and sales growth (0.046)	**SP2** Consider the current technology feasibility and labor safety in operation (0.036)
EV8 Develop waste reduction and energy efficiency program (0.138)	**EV4** Use eco-friendly material in the product and manufacturing process (0.034)	**EP2** Reduce the non-value-added activities (0.041)	**SP3** Develop a standard process to establish consistency across the organisation (0.035)
EV10 Control the emission of hazardous material (0.130)	**EV2** Increase the use of renewable material in product and process (0.033)	**EP7** Minimise the overall operation cost (0.039)	**SP5** Improve employee safety and health (0.035)
	EV3 Increase the usage of recycling waste material and product (0.029) **EV1** Increase the usage of recycle product (0.029)	**EP3** Improve manufacturing capability and flexibility (0.036)	**SP1** Improve work environment (0.028)
	EV7 Consider using easily degradable chemicals in product and production process (0.026)	**EP6** Reduce total production lead time (0.033)	**SP4** Improve relationship with communities and stakeholder (0.026)
	EV6 Reduce the consumption of energy and fuel (0.013)	**EP8** Quantity of material purchased fit to the planned quantities (0.032)	**SP8** Consider the direct social effect and community in product development (0.020)
		EP9 Consider the economic effect on the selection of the system (0.030)	**SP6** Collaborate with stakeholder regarding environmental issue (0.024)
		EP4 All raw materials and parts arrive within the delivery date (0.029)	

LESS IMPORTANT

Fig. 6. The Priority Level of Sustainable Manufacturing Practices

The social criterion with weight 0.245 is in third place after environmental and economic criteria. This criterion is concerned with the manufacturing firm's impact on the social system in which it operates and reflects how the manufacturing firms treat their workers, suppliers, clients, and the entire society. Even though this criterion seems to be less important compared to economic and environmental criteria, it should not be neglected. This criterion should be emphasized the same as environmental and economic because neglecting this dimension can have serious repercussions for organizational supply chains [XI].

These three criteria play their own role in manufacturing sustainability performance. Although the weight for each criterion might be different, consideration of all must be given to prevent less sustainable results. The ability of firms to manage the economic, environmental, and social impact on the environment is the primary key to success in long-term business strategy.

IV. Conclusion

Today's uncertain and competitive business environment has forced the manufacturing sector to seek flexible approaches in manufacturing strategies. Implementation of SMP has been recognized as one of the strategies to pursue business excellence. The identification of which practice is being implemented becomes a complex decision-making process. FAHP methodology has been used to identify and organize the process of implementation. Resulted from this methodology, the environmental aspect, which consists of an environmental conservation program and an environmental recycling and prevention program, appeared to be emphasized in the implementation of SMP. A priority list of decisions in SMP implementation is also presented, which may guide manufacturing practitioners in resource allocation, planning, and in formulating strategic initiatives.

V. Acknowledgements

The authors would like to express their gratitude to Universiti Teknikal Malaysia Melaka (UTeM) for funding support for the research under the research grant, INDUSTRI (URMG)/PRYM/FTKIP/2025/I00108.

Conflict of Interest:

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission, and declare no conflict of interest in the manuscript.

References

I. A. Bagherian, C. Laux and M. Kondala. : 'Transforming quality management: A fuzzy AHP-based approach to Quality 5.0 decision-making'. *Quality Management Journal*. vol. 33, no. 2, pp. 83-105. 2026. 10.1080/10686967.2025.2579156

II. A. Kumar, S. Luthra, S. K. Mangla and Y. Kazançoğlu. : 'COVID-19 impact on sustainable production and operations management'. *Sustainable Operation and Computer*. vol. 1, pp. 1–7. 2020. 10.1016/j.susoc.2020.06.001

III. I. Suwarna, I. Khasanah and A. Choerudin. : Sustainable operations management: evaluating green supply chain practices and their effect on competitive advantage'. *Journal Management & Economics Review (JUMPER)*. vol. 3, no. 8, pp. 465-478. 2026. 10.59971/jumper.v3i8.863

IV. K. B. Bour, A.J. Asafo, and B.O. Kwarteng. : 'Study on the effects of sustainability practices on the growth of manufacturing companies in urban Ghana'. *Heliyon*, vol. 5, no. 6, 2019. 10.1016/j.heliyon.2019.e01903

V. L. Huang, H. Liu, E. Oghenerobor and C. S. Chen. : 'Collaborating digitalization and green supply chain to promote green development of manufacturing firms–an analysis from a configurational perspective'. *Chinese Management Studies*. vol. 20, no. 8, pp. 2133-2155. 2026. 10.1108/CMS-08-2024-0570

VI. M. Etemad, S. Nazari-Shirkouhi, S. K. Chaharsooghi and K. Govindan. : 'Relationship between lean, agile, resilient and green paradigm and sustainable supply chain performance: an empirical investigation'. *Industrial Management & Data Systems*. pp. 1-36. 2026. 10.1108/IMDS-05-2025-0725

VII. M. Farrukh Shahzad, H. Liu and H. Zahid. : 'Industry 4.0 technologies and sustainable performance: do green supply chain collaboration, circular economy practices, technological readiness and environmental dynamism matter?' *Journal of Manufacturing Technology Management*. vol. 36, no. 1, pp. 1-22. 2025. 10.1108/JMTM-05-2024-0236

VIII. M. J. Cohen. : 'Does the COVID-19 outbreak mark the onset of a sustainable consumption transition?' *Sustainability: Science, Practice and Policy*. vol. 16, no. 1, pp. 1–3. 2020. 10.1080/15487733.2020.1740472

IX. M. Z. Yusup, W. H. W. Mahmood, M. R. Salleh and M. R. Muhamad. : 'The influence factor for the successful implementation of cleaner production: a review'. *Jurnal Teknologi (Sciences & Engineering)*, vol. 67, no. 1, 2014. 10.11113/jt.v67.2160

X. N. R. M. Alias, N. Hami and S.M. Shafie. : 'A case study analysis of sustainable manufacturing practice in Malaysian manufacturing firm'. *Journal of Technology and Operations Management*. vol. 13, no. 1, pp. 68-77. 2018. 10.32890/jtom2018.13.1.7

XI. S. J. H. Dehshiri. : 'Sustainable supplier selection based on a comparative decision-making approach under uncertainty'. *Spectrum of Operational Research*. vol. 3, no. 1, pp. 238-251. 2026. 10.31181/sor31202644

XII. S. Luthra, A. Kumar, E. K. Zavadskas, S. K. Mangla and J. A. Garza-Reyes. : 'Industry 4.0 as an enabler of sustainability diffusion in supply chain: an analysis of influential strength of drivers in an emerging economy'. *International Journal of Production Research*. vol. 58, no. 5, pp. 1505–1521. 2019. 10.1080/00207543.2019.1660828

XIII. S. Zighan, Z. Alkalha and L. Jum'a. : 'Barriers to circular economy transitions in emerging markets: insights from the GCC and implications for sustainable development.' *Sustainable Development*. vol. 34, pp. 210-225. 2026. 10.1002/sd.70177

XIV. S. H. Abdul-Rashid, N. Sakundarini, R.A.R. Ghazilla and R. Thurasamy. : 'The impact of sustainable manufacturing practices on sustainability performance: Empirical evidence from Malaysia'. *International Journal of Operations & Production Management*. vol. 37, no. 2, pp. 182-204. 2017. 10.1108/IJOPM-04-2015-0223

XV. W. H. W. Mahmood, M. N. Ab Rahman and B. M. Deros. : 'Green supply chain management in Malaysian aero composite industry'. *Jurnal Teknologi (Sciences and Engineering)*, vol. 59, pp. 13-17. 2012.