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AN INTEGRATED PYTHAGOREAN FUZZY MULTI-CRITERIA DECISION MAKING MODEL FOR BEST SUPPLIER SELECTION IN SUSTAINABLE AGILE MANUFACTURING

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Abstract. In modern supply chain management, selecting sustainable agile suppliers is essential. This approach integrates agile practices with sustainability principles to build resilient, eco-friendly supplier networks. It enhances competitiveness, reduces environmental impact, and supports effective supply chain risk management. By prioritizing environmental, social, and economic factors in supplier selection, organizations can form lasting partnerships that align with sustainability goals and remain adaptable to shifting market demands. This study aims to identify the optimal supplier for a Sustainable Agile Manufacturing process by incorporating insights from three decision-makers and evaluating five alternatives based on 20 specific criteria. In this article two integrated Multi-Criteria Decision Making (MCDM) model proposed within Pythagorean fuzzy (PF) environment to identify the optimal supplier for sustainable agile manufacturing. First, the Pythagorean fuzzy MEthod based on the Removal Effects of Criteria (MEREC) method is used to calculate objective criteria weights, followed by the Pythagorean fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to determine subjective criteria weights. Then, the Pythagorean fuzzy Measurement of Alternatives and Ranking according to COmpromise Solution (MARCOS) and Pythagorean fuzzy Multi-Attributive Border Approximation area Comparison (MABAC) methods are applied to finalize the selection of the most suitable supplier. The results of this study indicate that the 4th alternative is the optimal supplier for a sustainable, agile manufacturing process. Additionally, this article explores the interdependencies among criteria and provides comprehensive sensitivity and comparison analysis, along with insights into the managerial implications of this research.

Mathematics Subject Classification. 90-XX.

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1. Introduction

Sustainable agile manufacturing is a production methodology that prioritizes adaptability, promptness, and creativity in the manufacturing process. Sustainable agile manufacturing represents an evolution from the principles of lean manufacturing, which primarily focuses on cost reduction. The shift towards agile manufacturing emerged from the necessity for organizations to be more adaptable and responsive to customer needs. Unlike lean manufacturing, Sustainable agile manufacturing emphasizes flexibility to accommodate diverse customer demands. This shift highlights a return to a previous state where manufacturing had to respond to various pressures, potentially impacting costs and quality. Transitioning between lean and agile manufacturing poses a significant challenge in modern production environments [7]. In contrast to conventional manufacturing techniques, which frequently depend on large-scale production runs and inflexible procedures, Sustainable agile manufacturing emphasizes flexibility to satisfy shifting consumer needs and market dynamics. This method combines cutting-edge technology with efficient communication systems and empowered teams that can act quickly to make changes and make choices. Modular design, just-in-time manufacturing, and cross-functional cooperation are examples of agile concepts that manufacturers can quickly adopt to expand into new product lines, personalize orders, and maximize resource utilization. The fundamental tenets of agile manufacturing are customer-centricity and continuous improvement, which help businesses minimize waste and maximize efficiency while remaining competitive in a quick-paced global marketplace.

In today's rapidly evolving business landscape, a sustainable, agile manufacturing supplier is vital for several reasons. They can swiftly adapt to shifting market demands and customer preferences, adjusting product specifications, order quantities, and production timelines accordingly. Agile suppliers encourage innovation and collaboration within the supply chain, facilitating seamless communication and knowledge exchange. Moreover, by establishing contingency strategies and backup sourcing options, they help minimize risks related to supply chain disruptions.

In the current study, numerous questions emerge, such as:

(1) Why is sustainability essential in the supplier selection process for agile manufacturing?
(2) Which criteria are most suitable for sustainable supplier selection in an agile manufacturing environment?
(3) How does the integrated Multi-Criteria Decision-Making (MCDM) method support sustainable agile supplier selection under uncertainty?
(4) In what ways does this case study benefit society?
(5) What are the managerial implications of this study?

Sustainability is an important factor in supplier selection for agile manufacturing, as it encourages environmental responsibility, regulatory compliance, cost-effectiveness, and long-term stability. Suppliers that prioritize sustainability help reduce risks, improve brand reputation, and promote innovation, while contributing to a resilient supply chain capable of adapting quickly to market changes. This supports the flexibility and efficiency essential to agile manufacturing. With the help of 3 decision-makers opnion, 20 criteria and 5 alternatives employed in this article to select the optimal supplier. This article explores the interdependency between criteria, which helps to examine the relationships among them.This article presents two integrated Multiple Criteria Decision Making (MCDM) methodologies designed to address the uncertainty involved in supplier selection within the context of sustainable agile manufacturing, utilizing a Pythagorean fuzzy environment. In this article, two integrated decision-making models are employed within PF environment to evaluate criteria weights by combining both objective and subjective factors through the Pythagorean fuzzy MEthod based on the Removal Effects of Criteria (MEREC) and Pythagorean fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods. These methods are crucial for establishing reliable and precise criteria weights in Multi-Criteria Decision Making (MCDM), as they integrate data-driven insights with decision-maker's opinions. By combining Pythagorean fuzzy MEthod based on the Removal Effects of Criteria (MEREC) and Pythagorean fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL), a balanced weighting system is created for more accurate evaluations. Alternatives are ranked using the Pythagorean fuzzy Measurement of Alternatives

Table 1. List of abbreviation.

Abbreviation	Description
PF	Pythagorean fuzzy
MCDM	Multi-Criteria Decision Making
LVs	Linguistic Variables
MEREC	MEthod based on the Removal Effects of Criteria
DEMATEL	Decision-Making Trial and Evaluation Laboratory
MARCOS	Measurement of Alternatives and Ranking according to COmpromise Solution
MABAC	Multi-Attributive Border Approximation area Comparison
AHP	Analytic Hierarchy Process
COPRAS	Complex Proportional Assessment
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
PFNs	Pythagorean Fuzzy Numbers
PFS	Pythagorean Fuzzy Sets
DMs	Decision-Makers
DMEs	Decision-Making Experts
PFWFA	Pythagorean Fuzzy Weighted Fairly Aggregation
BAA	Border Approximation Area
UF	Utility Function

and Ranking according to COmpromise Solution (MARCOS) and Pythagorean fuzzy Multi-Attributive Border Approximation area Comparison (MABAC) methods, which are reliable tools for ranking analysis. These methods provide a flexible approach to managing both quantitative and qualitative data, ensuring that the ranking process can address the uncertainties and complexities often faced in decision-making, particularly in sustainable supplier selection for agile manufacturing.

In supplier selection for sustainable agile manufacturing, both subjective and objective criteria weights are essential. Subjective weights, which are typically derived from expert opinions or stakeholder input, provide qualitative insights into aspects like supplier reputation, flexibility, and alignment with sustainability goals. These subjective factors offer valuable experience-based assessments that, while difficult to quantify, are vital for ensuring that selected suppliers can meet the agile and sustainable demands of the industry.

In contrast, objective weights rely on quantifiable data such as cost, delivery performance, and quality metrics. These objective criteria offer a solid, data-driven foundation for comparison, ensuring that decisions are grounded in measurable performance indicators. By integrating both subjective and objective weights, a well-rounded and thorough evaluation framework is established, allowing decision-makers to choose suppliers that fulfill both operational requirements and strategic goals for sustainability and agility. This comprehensive approach helps organizations make optimal supplier selections that align with immediate production needs as well as long-term sustainability objectives. Besides this artcle explore the interdependency between criteria which helps to check the relation among criteria. The Table 1 below represents the abbreviation and their description.

1.1. Challenges in sustainable agile supplier selection

Balancing agility with sustainability in supplier selection involves various challenges. Maintaining competitive pricing while following sustainable practices can lead to higher costs, and ensuring high product quality may conflict with the speed required in agile systems. Financial limitations also hinder smaller, more agile suppliers from investing in sustainable technologies. Furthermore, the time needed to implement sustainable practices, such as waste reduction or using eco-friendly materials, can limit production flexibility, making it difficult to achieve both agility and sustainability.

1.2. Motivation and significance of the research

This research is driven by the increasing demand for companies to incorporate sustainable and agile practices into their supply chain management, particularly in choosing suppliers who adhere to these values. As businesses face mounting pressure to meet environmental and social obligations while staying competitive, selecting the right suppliers becomes essential. However, traditional supplier selection methods often fall short in addressing the complex and multi-dimensional aspects of sustainability and agility, leading to less optimal decisions. This study is motivated by the need for a more comprehensive, robust approach to decision-making that integrates both sustainability and agility, while also managing the uncertainties inherent in supplier evaluation. The significance of this research lies in its development of two integrated Pythagorean Fuzzy Multi-Criteria Decision-Making (MCDM) model, which is designed to tackle the challenges involved in sustainable agile supplier selection. By utilizing this advanced decision-making framework that incorporates fuzzy logic to manage uncertainty and imprecision, the study offers a more accurate, reliable, and adaptable method for evaluating suppliers. This model enables decision-makers to consider both objective and subjective criteria, such as environmental, social, and economic factors, which are crucial for achieving sustainability and agility in manufacturing processes.

Additionally, the research employs a variety of MCDM techniques, including PF-MEREC, PF-DEMATEL, PF-MARCOS, and PF-MABAC, to strengthen the decision-making process by taking into account different perspectives and the interactions among criteria. This comprehensive approach offers valuable insights for organizations seeking to improve their supply chain management, encourage innovation, and achieve sustainability goals. Ultimately, the study adds to the growing body of knowledge in sustainable supply chain management by presenting a well-organized and efficient methodology for selecting the most appropriate suppliers for sustainable agile manufacturing, thus enhancing operational efficiency and strengthening long-term competitive advantage.

To achieve the objectives, the remaining part of the article is structured as follows. A literature review is performed in Section 2. In the third section, the PF-MEREC, PF-DEMATEL, PF-MARCOS method, and PF-MABAC methods are expressed in details. The case study and result discussion are expressed in Section 4. The fifth section represents the sensitivity analysis and comparative analysis. Section 6 encompasses the managerial implications. The final Section 7 represents the conclusion of the research along with its limitations and future research of the study.

2. Literature review

In this section, existing literature on the supplier selection process for agile manufacturing is studied in detail, with particular focus given to the MCDM methods that related to our work. In today's dynamic business environment, companies face evolving customer demands, market fluctuations, and technological advancements. Sustainable Agile manufacturing supplier selection involves identifying and partnering with suppliers capable of responding quickly to market shifts, changes in product specifications, and fluctuating demand patterns. These suppliers possess attributes such as flexibility, responsiveness, innovation, and collaborative problem-solving capabilities. They can adjust production schedules, modify product designs, and streamline processes to meet evolving requirements efficiently. It is essential for maintaining competitiveness, driving innovation, and ensuring customer satisfaction in today's fast-paced business landscape.

Recently, numerous researchers have been focusing on the Sustainable agile manufacturing supplier selection process. Here, we present some of their research work. Sahu *et al.* applied a combined MCDM approach within a lean-agile-resilient-green framework in the Indian automotive sector [40]. Sheykhzadeh *et al.* utilized a hybrid decision-making framework to address the supplier selection problem, based on the case study of pharmaceutical industry [41].

Venugopal and Saleeshya address the Manufacturing system sustainability through lean and agile initiatives [48]. Agarwal *et al.* authored an article that explores how Industry 4.0 contributes to agile manufacturing to attain sustainable development goals [1]. Recently, Coimbra *et al.* in a paper discussed the factors contributing to agile success within an Irish manufacturing company [11]. Dursun and Ogunclu employed the Hierarchical

TOPSIS Method to conduct an agile Supplier Evaluation [13]. In his study, Goker looks at how agile outsourcing companies are chosen in the Turkish white goods market [22]. Again the Analytic Hierarchy Process (AHP) approach is used by David *et al.* to choose agile software practices [16]. Akhtar writes a review paper based on the selection of sustainable and agile manufacturing outsourcing partners [2]. Sahoo and Debnath applied the MABAC method within a fuzzy environment to identify the optimal location for implementing regenerative practices in tourism [39]. Kumar *et al.* evaluate performance criteria in agile supplier selection using the Fuzzy Decision Making Trial and Evaluation Laboratory (DEMATEL) technique [28]. Ghazvinian *et al.* have employed Multi-Criteria Structural Equation Modeling for Lean, agile, Resilient, Green, and Sustainable (LARGS) Supplier Selection in fuzzy environments [19]. Ecer and Dragan evaluate the effectiveness of insurance companies during the COVID-19 pandemic, specifically in healthcare services, using the MARCOS approach in a fuzzy environment [15]. To solve the sustainable circular supplier selection problem, Mishra *et al.* used an integrated Pythagorean fuzzy reasonably operator-based MARCOS technique [31]. Giri *et al.* applied an MCDM model to address the challenges associated with sustainable lithium-ion battery supply chains in electric vehicles in India [21]. Again, To select green suppliers for agribusiness, Puvska *et al.* combine fuzzy rough sets with LMAW and MABAC method [36]. Luo *et al.* employ a hybrid AFSA-MABAC approach for the selection of data products [30]. Chaurasiya and Jain utilized a hybrid PF-MCDM model to select a reliable hospital management system [10]. The MABAC model is used by Chakraborty *et al.* to select healthcare suppliers in uncertain scenarios [8]. Hajiaghaei *et al.* utilized the PF-TOPSIS method to select green suppliers within the food industry [23]. Chaurasiya and Jain used an integrated MCDM model within a PF environment to identify the optimal banking management software [9].

The Table 2 represents the summary of literature review.

2.1. Research gap

The literature review highlights several significant research gaps. Although various Multi-Criteria Decision-Making (MCDM) methods, including AHP, TOPSIS, DEMATEL, and COPRAS, have been widely used in recent years, there remains a strong need for an integrated MCDM approach that can deliver reliable ranking results while also clarifying interdependencies among criteria. This points to the necessity for hybrid decision-making models like MEREC-DEMATEL-MARCOS and MEREC-DEMATEL-MABAC, which could provide optimal solutions for supplier selection within a Pythagorean fuzzy environment. Additionally, no existing studies have thoroughly examined sustainable Agile manufacturing supplier selection through a case study incorporating a large number of criteria alongside these hybrid models, thereby exposing another critical research gap.

2.2. Contribution of this research

The key features of our contribution to this manuscript are enumerated as follows:

- This study identifies the essential criteria for the optimal selection process of suppliers in Sustainable Agile manufacturing.
- To convey the uncertainty associated with supplier selection in the sustainable agile manufacturing process, an integrated Multiple Criteria Decision Making (MCDM) methodologies has been developed within a Pythagorean fuzzy environment.
- An aggregation operator is employed to determine the aggregated decision matrix within the Pythagorean fuzzy environment.
- In this paper, both subjective and objective criteria weights are evaluted by the help of PF-DEMATEL and PF-MEREC method.
- This article evaluates the interdependencies among the criteria.
- This research employs the PF-MARCOS and PF-MABAC methods to rank the alternatives.
- Sensitivity analysis, comparison analysis and managerial implications are also expressed in this research.

TABLE 2. Summary of literature review.

Case study	Ref. no	Uncertainty model	Method used	Key features
Automotive sector	[40]	–	Integrated MCDM model	Criteria evaluation and optimal supplier evaluated by the help of hybrid model
Pharmaceutical industry	[41]	Fuzzy	BWM-ARAS	Criteria employed along with optimal supplier selected
Manufacturing system	[48]	–	AHP-ANP	Methodology applied nicely along with ranking evaluated
Agile manufacturing	[1]	–	–	Industrial contribution for Agile manufacturing express in well manner
Irish manufacturing company	[11]	–	–	Factors contributing to agile success expressed in well manner
Agile supplier evaluation	[13]	–	TOPSIS	Criteria consider and Agile optimal supplier evaluation by MCDM model
Agile company selection	[22]	–	–	Briefly express about Agile outsourcing company select in white good market
Agile software practices	[16]	–	AHP	Employed MCDM method to choose Agile software practices
Sustainable and agile manufacturing	[2]	–	–	Express review of work related to Sustainable and agile manufacturing
Optimal location selection	[39]	Fuzzy	MABAC	Decision-making model employed for Optimal location selection
Agile supplier selection	[28]	Fuzzy	DEMATEL	Criteria evaluated and decision model employed for Agile supplier selection
LARGS supplier selection	[19]	Fuzzy	Multi-criteria structural equation	LARGS supplier selection by the help of structural model
Effectivness of insurance companies	[14]	Fuzzy	MARCOS	Effectivness of insurance companies evaluated by the help of MCDM model
Sustainable circular supplier	[31]	PF	CRITIC-PIPRECIA-MARCOS	Criteria employed along with integrated MCDM model employed for Sustainable circular supplier selection
Sustainable lithium-ion battery	[21]	–	GTMA	Criteria consider and Sustainable lithium-ion battery evaluated by MCDM model
Green supplier selection	[36]	Fuzzy rough set	LMAW-MABAC	Criteria evaluation and MCDM model applied in Green supplier selection process
Selection of data products	[30]	–	AFSA-MABAC	Selection of data products by integrated method
Reliable hospital management system	[10]	PF	MEREC-SWARA-MARCOS	Criteria employed along with hybrid method used for the hospital management system
Healthcare supplier selection	[8]	–	MABC	Criteria used and MCDM model used for supplier selection
Green supplier selection	[23]	PF	TOPSIS	Criteria used and MCDM method employed for Green supplier selection
Banking management software selection	[9]	PF	MEREC-SWARA-COPRAS	Criteria evaluted and integrated model used for BMSS
Our proposed integrated model		PF	MEREC-DEMATEL-MARCOS and MEREC-DEMATEL-MABAC	Maximum criteria evaluation and integrated MCDM model employed to select an optimal supplier

3. RESEARCH METHODOLOGY

3.1. Sustainable agile manufacturing

In agile manufacturing, sustainability is a crucial development in industrial operations, where social responsibility, environmental care, and economic viability come together. Throughout the production process, agile manufacturing promotes sustainable practices by emphasizing efficiency, adaptability, and response to shifting market needs. To reduce its influence on the environment, it places a high priority on waste reduction, resource optimization, and the integration of renewable energy sources has become a focus of recent research, with many researchers working on this topic [20, 25, 37]. Additionally, ethical labor practices, community involvement, and fair resource allocation are encouraged by sustainable agile manufacturing. Agile manufacturing strives for long-term success while reducing social injustice and environmental degradation by incorporating sustainability concepts. This all-encompassing strategy advances corporate resilience while also advancing the more general objective of building a more just and sustainable international economy.

3.2. Preliminary knowledge

In the fields of fuzzy logic and mathematics, a fuzzy set is fundamental. To address the ambiguity and uncertainty that arise in decision-making situations, Lotfi Zadeh [53] created this idea in the 1960s. Unlike classical sets, which maintain a binary membership structure in which items are either members or are not, fuzzy sets allow members to have membership degrees between 0 and 1. Fuzzy sets are primarily concerned with the membership degree in uncertain situations [15]. It is unable to handle the non-membership degree in unclear circumstances. To get around this restriction, Atanassov [5] proposed Intuitionistic Fuzzy Sets (IFS) as a workable way to deal with the ambiguity around non-membership functions. It is difficult to handle this kind of circumstance once more. Then Zhang *et al.* [54] devised Pythagorean Fuzzy Sets (PFS) to get around this problem. It entails taking the square sum of the membership and non-membership functions and making sure that the total of their square sums is less than or equal to one that is

$$0 \leq \alpha^2 + \beta^2 \leq 1.$$

Here α represents the degree of membership and β represents the degree of non-membership.

3.2.1. Properties of Pythagorean fuzzy numbers

The properties of the PFNs are as follows [31,52].

Suppose $\tilde{x} = (\alpha, \beta)$, $\tilde{x_1} = (\alpha_1, \beta_1)$, and $\tilde{x_2} = (\alpha_2, \beta_2)$, be three PFNs. Then, the following operational rules apply to these PFNs:

(1) $\tilde{x}^c = (\beta, \alpha)$;
(2) $\tilde{x}_1 + \tilde{x}_2 = (\sqrt{\alpha_1^2 + \alpha_2^2 - \alpha_1^2 * \alpha_2^2}, \beta_1 * \beta_2)$;
(3) $x_1 * x_2 = (\alpha_1 * \alpha_2, \sqrt{\beta_1^2 + \beta_2^2 - \beta_1^2 * \beta_2^2})$;
(4) $\lambda * x = (\sqrt{1 - (1 - \alpha^2)^\lambda}, (\beta)^\lambda),\ \ \lambda > 0$;
(5) $x^\lambda = ((\alpha)^\lambda, \sqrt{1 - (1 - \beta^2)^\lambda}),\ \ \lambda > 0$.

3.2.2. Decision-makers weight evaluation

In determining decision-makers' weight, the primary criterion for assessing their significance involves assigning a significance rating. This rating is established through the utilization of linguistic variables (LVs) and articulated in the form of Pythagorean Fuzzy Numbers (PFNs). Let $\tilde{x}_r = (\alpha_r, \beta_r)$ denote the Pythagorean Fuzzy Number (PFN) of the r-th Decision-Making Expert (DME). The expression for determining the weight of r-th DME is as follows [10]:

$$w_r = \frac{\alpha_r^2\left(2 - \alpha_r^2 - \beta_r^2\right)}{\sum_{r=1}^{l}[\alpha_r^2(2 - \alpha_r^2 - \beta_r^2)]}. \tag{1}$$

3.2.3. Pythagorean fuzzy weighted fairly aggregation operator

Let $\tilde{x}_j = (\alpha_j, \beta_j)$ be a set of Pythagorean fuzzy numbers (PFNs) where $j = 1$ to s.

Then, the "Pythagorean Fuzzy Weighted Fairly Aggregation (PFWFA)" operator is defined as [31]:

$$\begin{aligned}\mathrm{PFWFA}(x_1, x_2, \ldots, x_m) &= (w_1 * x_1)\tilde{\otimes}(w_2 * x_2)\tilde{\otimes}(w_3 * x_3)\tilde{\otimes}\cdots\tilde{\otimes}(w_s * x_s)\\ &= \sqrt{\left(\frac{\prod_{j=1}^{s}({\alpha_j}^2)^{w_j}}{\prod_{j=1}^{s}({\alpha_j}^2)^{w_j} + \prod_{j=1}^{s}({\beta_j}^2)^{w_j}} * \left(1 - \prod_{j=1}^{s}\left(1 - {\alpha_j}^2 - {\beta_j}^2\right)^{w_j}\right)\right)},\end{aligned}$$

$$\sqrt{\left(\frac{\prod_{j=1}^{s}({\beta_j}^2)^{w_j}}{\prod_{j=1}^{s}({\alpha_j}^2)^{w_j}+\prod_{j=1}^{s}({\beta_j}^2)^{w_j}} * \left(1-\prod_{j=1}^{s}\left(1-{\alpha_j}^2-{\beta_j}^2\right)^{w_j}\right)\right)}. \quad (2)$$

Here, $\tilde{\otimes}$ denotes the aggregation operation applied across each weighted Pythagorean fuzzy number $w_j * x_j$ for $j = 1, 2, \ldots, s$. Additionally, each weight $w_j > 0$, and the weights satisfy the condition $\sum_{j=1}^{s} w_j = 1$.

3.2.4. *Score function*

The score function for the Pythagorean fuzzy numbers is defined as [50]

$$\text{Score}(\tilde{s}_{ij}) = \frac{1}{2}\left(\left(\alpha_{ij}^2 - \beta_{ij}^2\right) + 1\right), \quad i = 1, 2, \ldots, m, \quad j = 1, 2, \ldots, n \quad (3)$$

where $\tilde{s}_{ij} = (\alpha_{ij}, \beta_{ij})$ be a Pythagorean fuzzy number.

3.3. Approach to determine combined weights

3.3.1. *Objective weights based on Pythagorean fuzzy MEREC method*

The steps of this method are as follows

Step 1. An Aggregated decision matrix created, based on 3 decision-makers opnion. where the decision-makers consider 20 criteria and 5 alternatives along with the help of equations (1), (2) and Table 4 to construct this matrix.

Step 2. Normalized the aggregated decision-matrix.
Here the aggregated PF-decision matrix is converted into crisp decision matrix with help of equation (3). Then the elements of each decision-matrix are nomalized by using the formula below [9]

$$n_{ij} = \begin{cases} \dfrac{\min_i(x_{ij})}{x_{ij}}, & \text{for beneficial type criteria} \\[2ex] \dfrac{x_{ij}}{\max_i(x_{ij})}, & \text{for non-benificial type criteria.} \end{cases} \quad (4)$$

Step 3. Compute the entire performance of the alternatives. A logarithmic function with equal weighting for each criterion is used in this step to evaluate the overall performance. The formula is express in below [9,10]

$$\Omega_i = \ln\left(1 + \left(\frac{1}{n}\sum_{j=1}^{n}|\ln(n_{ij})|\right)\right). \quad (5)$$

Step 4. Evaluate the behavior of the alternatives by eliminating each criterion. This step is similar to the previous one, except that in this step, the evaluations for each alternative are determined by excluding one criteria at a time. Suppose we have n sets of appraisals corresponding to n criteria. Let Ω'_{ij} denote the overall evaluation of the i-th alternative when the j-th criterion is excluded. The formula is presented below

$$\Omega'_{ij} = \ln\left(1 + \left(\frac{1}{n}\sum_{k,k\neq j}|\ln(n_{ik})|\right)\right). \quad (6)$$

Step 5. Calculate the summation of absolute deviations. For this we use the equations (5), (6). The formula is expressed in below

$$M_j = \sum_{i=1}^{m}\left|\Omega'_{ij} - \Omega_i\right|. \quad (7)$$

Step 6. In this step we take the help of M_J to get the objective weight of each criterion. The formula is express in below

$$W_j^o = \frac{M_j}{\sum_{j=1}^{n} M_j}. \tag{8}$$

3.3.2. Subjective weights based on Pythagorean fuzzy DEMATEL method

The steps of this method are as follows [43]

Step 1. An aggregated initial direct-relation matrix constructed.

While constructing this matrix, the three decision-makers utilize specific equations (1), (2) and refer to the Table 4 for assistance.

The aggregated initial direct-relation matrix is expressed below

$$\tilde{E}^{agg} = \begin{bmatrix} [0,0] & [\alpha_{12}{}^{agg}, \beta_{12}^{agg}] & \dots & [\alpha_{1n}^{agg}, \beta_{1n}^{agg}] \\ [\alpha_{21}^{agg}, \beta_{21}^{agg}] & [0,0] & \dots & [\alpha_{2n}^{agg}, \beta_{2n}^{agg}] \\ \dots & \dots & \dots & \dots \\ [\alpha_{n1}^{agg}, \beta_{n1}^{agg}] & [\alpha_{n2}^{agg}, \beta_{n2}^{agg}] & \dots & [0,0] \end{bmatrix}. \tag{9}$$

Step 2. Construct the aggregated initial direct-relation crisp decision matrix.

In this step, we take the help of score function equation (3) to convert the aggregated decision matrix into crisp decision matrix.

$$B = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1n} \\ \dots & \dots & \dots & \dots \\ b_{n1} & b_{n2} & \dots & b_{nn} \end{bmatrix}. \tag{10}$$

Step 3. Evaluation of normalized direct-relation matrix.

The normalized direct-relation matrix is evaluated by using the formula below

$$N = B * (\delta) \tag{11}$$

where

$$\delta = \frac{1}{\max\limits_{1<i<n} \sum_{j=1}^{n} |b_{ij}|}. \tag{12}$$

Step 4. The Total influence matrix $\tilde{T}$ is obtained by using the formulas are expressed below

$$T = N * (1 - N)^{-1} = \begin{bmatrix} t_{11} & \dots & t_{1n} \\ \dots & \dots & \dots \\ t_{n1} & \dots & t_{nn} \end{bmatrix}. \tag{13}$$

Step 5. Evaluate the value of the row sum (R_i) and column sum (C_j) where $R_i = \sum_{j=1}^{n} t_{ij}$ and $C_j = \sum_{i=1}^{n} t_{ij}$.

Step 6. Prominence and Relation matrix evaluation.

When $i = j$, both the prominence and relation values are determined using R_i and C_i. The prominence value is calculated as $R_i + C_i$, while the relation value is calculated as $R_i - C_i$. This approach further classifies the criteria into cause and effect groups: if $R_i - C_i$ is positive, the criteria belongs to the cause group; if $R_i - C_i$ is negative, it belongs to the effect group.

Step 7. Establish the interdependency relation.

In this step, we take the help of the Total influence matrix (T) to check the interdependency between criteria. If any value of the element t_{ij} of the matrix T exceeds the threshold value, there is an interdependency between the i-th criterion and the corresponding j-th criterion. If the value of t_{ij} is below the threshold value, then no interdependency exists between these criteria [38].

The formula express below to determine the threshold value (δ) [29]

$$\delta = \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{[t_{ij}]}{N}. \tag{14}$$

Here N is defined as the number of elements present in the matrix (T).

Step 8. The subjective weights are defined by using the formula provided below [12]

$$w_j = \sqrt{(R_j + C_j)^2 + (R_j - C_j)^2} \tag{15}$$

$$W_j^{\text{sub}} = \frac{w_j}{\sum_{j=1}^{n}(w_j)}. \tag{16}$$

Step 9. Evaluate the integrated criteria weights by combining both subjective and objective assessments. The formula to calculate an integrated weight for each criterion is expressed in below [10]

$$W_j = \frac{W_j^{\text{obj}} * W_j^{\text{sub}}}{\sum_{j=1}^{n} W_j^{\text{obj}} * W_j^{\text{sub}}} \tag{17}$$

where $\sum_{j=1}^{n} W_j = 1$ and $W_j \in [0, 1]$.

3.4. Approach to determine the alternatives ranking

3.4.1. Pythagorean fuzzy MARCOS method

The MAROSC method is a decision-making approach frequently utilized in MCDM problems. It is intended to assist in assessing and ranking alternatives according to various criteria or attributes, which are often subjective and challenging to measure. It is based on measuring options and then ranking them. This method contributes to an organized decision-making process by evaluating different possibilities and ranking them according to particular standards. Stevic *et al.* developed a method that is commonly known as the MARCOS methodology [45]. This technique serves as a robust decision-making tool; Ecer and Pamucar employed the MARCOS method within an intuitionistic fuzzy environment to assess the performance during the COVID-19 pandemic [14]. Here we employed the MARCOS method within the Pythagorean fuzzy environment.

The steps are express in below

Step 1. Initial decison matrix constructed.

With the help of 3 decision-makers opinions and the help of Table 4 an initial decision matrix constructed.

Step 2. Construction of aggregated PF decision matrix

$$\tilde{X} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \end{bmatrix} \tag{18}$$

where $\tilde{x}_{ij} = (\alpha_{ij}, \beta_{ij})$, $i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$.

Step 3. Evaluation of the aggregated normalized PF decision matrix [35]

$$\tilde{n}_{ij} = \begin{cases} \tilde{x}_{ij} = (\alpha_{ij}, \beta_{ij}) & \text{if } j \in B \\ \tilde{x}_{ij}^{c} = (\beta_{ij}, \alpha_{ij}) & \text{if } j \in C \end{cases} \tag{19}$$

where B standards are for beneficial, and C standards are for non-beneficial criteria.

Step 4. Evaluation of PF-ideal and PF-anti ideal solution [31]

$$\tilde{x}_{eej} = \begin{cases} \max_i(\alpha_{ij}), \min_i(\beta_{ij}) & \text{if } j \in B \\ \min_i(\alpha_{ij}), \max_i(\beta_{ij}) & \text{if } j \in C \end{cases} \tag{20}$$

$$\tilde{x}_{ej} = \begin{cases} \min_i(\alpha_{ij}), \max_i(\beta_{ij}) & \text{if } j \in B \\ \max_i(\alpha_{ij}), \min_i(\beta_{ij}) & \text{if } j \in C \end{cases} \tag{21}$$

where B standards for benificial and C standards for non-benificial type criteria.

Step 5. Extend the PF normalized decision matrix [49].

By the help of ideal and anti-ideal solution the matrix $\tilde{M}$ extended in the following form

$$\tilde{M} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \\ \tilde{x}_{ee1} & \tilde{x}_{ee2} & \dots & \tilde{x}_{een} \\ \tilde{x}_{e1} & \tilde{x}_{e2} & \dots & \tilde{x}_{en} \end{bmatrix} \tag{22}$$

where $\tilde{x}_{eej}$ and $\tilde{x}_{ej}$ represent the ideal and anti-ideal solution that we get from the previous step.

Here $\tilde{x}_{ij} = (\alpha_{ij}, \beta_{ij})$ $i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$.

Step 6. Aggregated weighted normalized PF decision matrix constructed.

The weighted aggregated normalized matrix is constructed by following the properties of PFNs, which are present in Section 3.2.1. The formula is expressed below

$$\tilde{V} = W_j * \tilde{M}_{ij} \tag{23}$$

where W_j is the weight of the criteria and M_{ij} be the extended PF normalized decision matrix.

Step 7. Evaluation of utility degrees

$$k^+ = \frac{S_i}{S_{eej}} \text{ and } k^- = \frac{S_i}{S_{ej}} \tag{24}$$

where S_{eej} = sum of the score values of $(\tilde{v}_{eej})$, S_{ej} = sum of the score values of $\tilde{v}_{ej}$ and $S_i = \sum_{j=1}^{n} \text{score}\,(\tilde{V}_{ij})$, $i = 1, 2 \dots m$.

Step 8. Evaluation of utility function.

The formula for utility function (UF) is expressed below

$$F(k_i) = \frac{k_i^+ + k_i^-}{1 + \frac{1 - F(k_i^+)}{F(k_i^+)} + \frac{1 - F(k_i^-)}{F(k_i^-)}} \tag{25}$$

where

$$F\big(k_i^+\big) = \frac{k_i^-}{k_i^+ + k_i^-}$$
$$F\big(k_i^-\big) = \frac{k_i^+}{k_i^+ + k_i^-}.$$

Then rank the alternatives according to the crisp value of these utility functions. Alternative with the maximimum value of utility function (UF) is treated as the optimal alternative.

3.4.2. Pythagorean fuzzy MABAC method

The MABAC method is especially useful in complex decision-making situations where evaluating alternatives across multiple criteria is crucial. Known for its dependable and consistent results, MABAC is also versatile, allowing it to accommodate various data types, which makes it highly suitable for prioritizing and ranking different options. As a multi-criteria decision-making tool, MABAC enables systematic analysis and ranking across diverse attributes, enhancing the overall assessment process. Initially proposed by Pamučar and Ćirović [32], its effectiveness has been praised. An approach integrating interval-valued intuitionistic fuzzy sets with MABAC algorithms was subsequently presented by Xue *et al.* to address material selection problems with insufficient weight information [51]. Jafari and Khanachah used an integrated MABAC method to assess supplier resilience and knowledge sharing within a Pythagorean fuzzy environment [24]. Chakraborty *et al.* applied the MABAC model to select healthcare suppliers within the fuzzy, environments [8]. Additionally, the multiple attribute group decision-making strategy based on the Pythagorean fuzzy Choquet integral was employed by Peng and Yang [35]. In this study, we apply the MABAC technique within the Pythagorean fuzzy environment to choose the optimal supplier for sustainable agile manufacturing. The steps are expressed in below

Step 1. First, we prepare an initial decision matrix with the help of 3 decision-makers opinions and the LVs present in Table 4.

Step 2. Aggregated decision matrix constructed.

An aggregated decision-matrix constructed with the helps of 3 decision-makers opnion and the help of equations (1), (2). The structure of this matrix be similar as like the previous Step-2 of the PF-MARCOS method.

Step 3. Next, we generate the normalized decision matrix. The value of each n_{ij} are determined by using the following equations [35]

$$\tilde{n}_{ij} = \begin{cases} (\alpha_{ij}, \beta_{ij}) & \text{if } j \in B \\ (\beta_{ij}, \alpha_{ij}) & \text{if } j \in C \end{cases}. \tag{26}$$

Here B standards for beneficial and C standards for cost type/non-beneficial type criteria.

Step 4. Compute the components of the weighted normalized matrix (V).

$V_{ij} = W_j * (\tilde{n}_{ij})$, $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$; where n_{ij} is the elements of the normalized matrix and W_j represents the criteria weights. This multiplication follows the properties of PFNs as express in Section 3.2.1

$$\tilde{V} = \begin{bmatrix} \tilde{v}_{11} & \tilde{v}_{12} & \ldots & \tilde{v}_{1n} \\ \tilde{v}_{21} & \tilde{v}_{22} & \ldots & \tilde{v}_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ \tilde{v}_{m1} & \tilde{v}_{m2} & \ldots & \tilde{v}_{mn} \end{bmatrix} = \begin{bmatrix} w_1 * (\tilde{n}_{11}) & w_2 * (\tilde{n}_{12}) & \ldots & w_n * (\tilde{n}_{1n}) \\ w_1 * (\tilde{n}_{21}) & w_2 * (\tilde{n}_{21}) & \ldots & w_n * (\tilde{n}_{2n}) \\ \ldots & \ldots & \ldots & \ldots \\ w_1 * (\tilde{n}_{m1}) & w_2 * (\tilde{n}_{m2}) & \ldots & w_n * (\tilde{n}_{mn}) \end{bmatrix} \tag{27}$$

where $\tilde{n_{ij}} = (\alpha_{ij}, \beta_{ij})$ and $v_{ij} = (\alpha'_{ij}, \beta'_{ij})$.

Step 5. Determining the BAA matrix (G) [26,35].

The Border Approximation Area (BAA) matrix is determined using the formula given below

$$\tilde{g}_j = \left(\prod_{i=1}^{m} \tilde{v}_{ij}\right)^{\frac{1}{m}}. \tag{28}$$

Equation (28) is also satiesfies the properties (Sect. 3.2.1) of Pythagorean Fuzzy Numbers (PFNs).

Here $\tilde{V}$ denotes the elements of the weighted normalized decision matrix, where each element of this matrix is represented by $\tilde{v}_{ij}$, and m represents the number of alternatives.

After computing the value $\tilde{g}_j$ for each criterion, a BAA matrix is generated in the following manner [32]:

$$\begin{matrix} C_1 & C_2 & \ldots & C_n \end{matrix} \tag{29}$$

$$\tilde{G} = \begin{bmatrix} \tilde{g}_1 & \tilde{g}_2 & \ldots & \tilde{g}_n \end{bmatrix}. \tag{30}$$

Step 6. Distance from the Border Approximation Area (Q Matrix).

In this step, we take the help of the score function equation (3) to convert both $\tilde{V}$ and $\tilde{G}$ matrix into the crisp matrix. The distance of the alternatives from the border approximation area (BAA) is determined as follows

$$Q = V - G = \begin{bmatrix} q_{11} & q_{12} & \cdots & q_{1n} \\ q_{21} & q_{22} & \cdots & q_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ q_{m1} & q_{m2} & \cdots & q_{mn} \end{bmatrix} \tag{31}$$

where

$$q_{ij} = \begin{cases} d(v_{ij}, g_j) > 0 & \text{for } v_{ij} > g_j \\ 0 & \text{for } v_{ij} = g_j \,. \\ d(v_{ij}, g_j) < 0 & \text{for } v_{ij} < g_j \end{cases} \tag{32}$$

The border approximation region may be associated with alternatives A_i. The approximation region can be broken down into three sections: the higher approximation area (G^+), the lower approximation area (G^-), and the border approximation area (G). Where the upper approximation area (G^+) contains all ideal alternatives and lower approximation area (G^-) contains all the anti-ideal alternatives.

$$A_i \in \begin{cases} G^+ & \text{if } q_{ij} > 0 \\ G & \text{if } q_{ij} = 0 \,. \\ G^- & \text{if } q_{ij} < 0 \end{cases} \tag{33}$$

From the above equation, it is clear that if the value of $q_{ij} > 0$, then it lies in the upper approximation area (G^+) and the alternative A_i is considered as an ideal alternative. Conversely, if the value of $q_{ij} < 0$ then it lies in lower approximation area (G^-), then the alternative is consider as an anti-ideal alternative. If $q_{ij} = 0$ then A_i belongs to the border approximation area (G).

Step 7. Ranking the alternatives.

Next, the alternatives ranking are obtained by following the formula below

$$F_i = \sum_{j=1}^{n} q_{ij}, \ i = 1, 2, \ldots, m. \tag{34}$$

Here n is the number of criteria, and m is the number of alternatives.

4. Case study and results discussion

In this segment, we examine a case study concerning the selection of the best suppliers in a sustainable agile manufacturing process. To assess the indicators and options, a panel of three decision-making experts (DMEs) named D1, D2 and D3 is established. These decision makers come from diverse backgrounds, each possessing extensive experience in their respective fields. They are proficient in decision-making methodologies and exhibit robust expertise in various agile supplier selection tasks. Their collective knowledge and skill set ensure a comprehensive evaluation of supplier alternatives, contributing to the effectiveness and efficiency of the supplier selection process within the sustainable agile manufacturing framework. In this case study, the decision-makers assess 20 criteria for suppliers, presented in Table 6. Each criterion is associated with five alternatives, denoted as M1, M2, M3, M4, and M5. The evaluation involves a thorough consideration of these criteria to determine the most suitable supplier or alternative for the given requirements. In this case study, two different integrated PF-MCDM models are used to evaluate the optimal Agile supplier. Figure 1 below illustrates the design of this model.

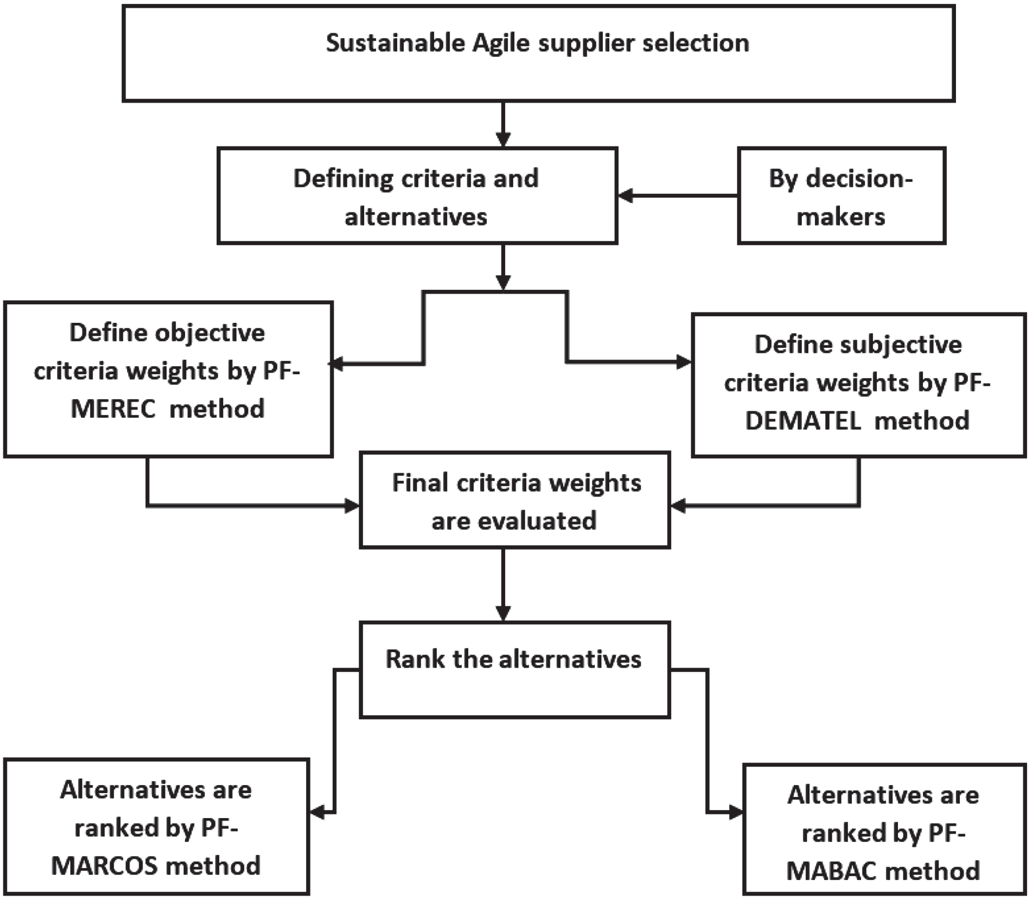

FIGURE 1. Framework for selecting the sustainable Agile supplier.

TABLE 3. Information about decision-makers.

Decision makers	Educational degree	Field	Position	Overall expericene
D1	Ph.D	Acedemia	Researcher	11
D2	M.S	Agile industry	Senior executive officer	12
D3	Ph.D	Acedemia	Researcher	14

In this case study, we include three decision-makers, whose educational qualifications and relevant experience appear in Table 3. These experts are assigned specific tasks: (i) evaluating the criteria, (ii) selecting linguistic variables, and (iii) creating a decision-making table. This team is assembled to conduct two main assessments: evaluating sustainable agile manufacturing practices and assessing criteria for potential alternatives. Each expert (decision-maker) is selected based on their relevant role in the field and brings over 10 years of experience in the manufacturing industry.

Table 4 provided outlines the LVs, indicating the importance of DMEs and associated criteria, which are subsequently transformed into PFNs.

TABLE 4. Linguistic variables and their corresponding Pythagorean fuzzy numbers.

LVs	PFNs
Absolutely good (AG)	$(0.97, 0.21, 0.122)$
Very very good (VVG)	$(0.90, 0.25, 0.357)$
Very good (VG)	$(0.86, 0.30, 0.413)$
Good (G)	$(0.80, 0.36, 0.480)$
Moderate good (MG)	$(0.75, 0.40, 0.527)$
Moderate (M)	$(0.70, 0.50, 0.509)$
Moderate bad (MB)	$(0.60, 0.65, 0.466)$
Bad (B)	$(0.45, 0.70, 0.5545)$
Very bad (VB)	$(0.35, 0.80, 0.487)$
Absolutely bad (AB)	$(0.20, 0.90, 0.387)$

TABLE 5. Weight of DMs.

DMs	LVs	PFNs	Weights
D1	VG	$(0.86, 0.3)$	0.337
D2	G	$(0.80, 0.36)$	0.307
D3	VVG	$(0.90, 0.25)$	0.356

The weight of the 3 decision maker is determined by utilizing LVs which is express in Table 4 and equation (1), as depicted in Table 5 below.

According to the decision maker's preferences, the criteria are listed below in Table 6.

In the Table 6 "B" indicates beneficial-type criteria, and "C" indicates non-beneficial or cost-type criteria.

Table 7 below is created by incorporating data from Table 4, which includes five alternatives and the opinions of three decision-makers for each criteria.

Table 8 express the aggregated PF decision matrix which is constructed with the help of Table 7 and equations (1), (2).

The normalized aggregated decision matrix 9 is constructed with the help of Table 8 and equation (4).

Table 10 represent the overall performance of the alternatives which is constructed with the helps of Table 9 and equation (5).

The Table 11 below is constructed with the help of Table 10 and equation (6).

With the help of Table 11 and equation (7) the Absolute deviation evaluated which is express in below.

Absolute deviation (M_j) value = (0.070, 0.013, 0.014, 0.017, 0.012, 0.011, 0.020, 0.025, 0.007, 0.014, 0.023, 0.011, 0.019, 0.021, 0.086, 0.014, 0.016, 0.063, 0.020, 0.051).

Table 12 represents the objective criteria weights which are expressed with the help of equation (8).

Next, for subjective weight we take the helps of the PF-DEMATEL method which is express in Section 3.3.2.

Table 13 below represent the initial direct-relation matrix which is evaluated based on 3 decision-makers opinions.

Table 14 below shows the aggregated direct influence matrix which is constructed with the help of Table 13 and equations (2) and (9).

Table 15 represents the Aggregated normalized direct influence crisp decision matrix which is constructed with the help of Table 14 and equations (10)–(12).

The Total influence matrix Table 16 is evaluated below with the help of Table 15 and equation (13).

Table 17 below express the prominence and Relation value which is constructed with the help of Step-6 of the PF-DEMATEL method which is express in Section 3.3.2.

TABLE 6. Criteria for Sustainable Agile supplier selection.

Sl.No.	Aspects	Criteria	Type	References
1	Economic	Product price	C	Akhtar *et al.* [3], Kabus *et al.* [27], Garg and Sharma [18]
2		Product quality	B	Akhtar *et al.* [3]
3		Financial capability	B	Tesic *et al.* [46], Alrasheedi *et al.* [4], Mishra *et al.* [31]
4	Flexibility	Production flexibility and capability	B	Akhtar *et al.* [3], Awasthi *et al.* [6]
5		Delivery flexibility	B	Akhtar *et al.* [3], Garg and Sharma [18]
6		Collaboration with partners	B	Sheykhzadeh *et al.* [41]
7		Market sensitivity	B	B.S. Patel *et al.* [33,34]
8		Sourcing flexibility	B	Akhtar [2]
9	Environmental	Green manufacturing process	B	Akhtar [2]
10		Green Reserch and Development	B	Akhtar [2], Sinha and Anand [42]
11	Social	Social welfare and community development	B	Akhtar [2], Garg and Sharma [18]
12		Multi-skilled and flexibility workforce	B	Akhtar [2]
13		training education and community development	B	Galankashi *et al.* [17]
14		Customer satisfaction	B	B.S. Patel *et al.* [33,34]
15		Risk management	C	By decision maker
16		Information and communication technology	B	Venugopal and Saleeshya [48]
17		Innovation capability	B	Sonar *et al.* [44]
18	Operational management	Use of harmful materials	C	Mishra *et al.* [31]
19		Buyer-supplier relationship	B	Kumar *et al.* [28]
20		Poor Quality Management Systems	C	By decision maker

Figure 2 displays the Prominence and Relation diagram. From the above Table 17 and Figure 2, it is evident that criteria C1, C15, C18, and C20 belongs to the Effect group, while the remaining criteria belong to the Cause group. Using equation (14), we find the threshold value (δ) to be 0.3442. To analyze the interdependencies between criteria, we refer to the total influence matrix in crisp terms and the δ value. If any element t_{ij} of matrix T 16 is greater than the δ value, then the criterion in the ith row influences the criteria in the jth column, establishing an interdependency relation. Conversely, if δ is greater than t_{ij}, then the criteria in the ith row does not influence the corresponding criteria in the jth column, which expresses there is no interdependency relation exist between them. For example, in matrix T, $t_{61}(0.3561) > \delta(0.3442)$, indicating that C6 impacts C1. Similarly, $t_{31}(0.3369) < \delta(0.3442)$ shows that C3 does not influence C1, as its value is below the threshold value. In this way, all relations based on the threshold value and matrix T can be evaluated.

By taking the help of Table 17 and equations (15) and (16), the subjective criteria weight evaluated which is express in Table 18.

Table 19 represents the final criteria weights which are evaluated with the help of both objective (Tab. 12), subjective (Tab. 18) criteria weights, and the help of equation (17).

Figure 3 below presents the graphical representation of the criteria weights.

Next, we take the help of PF-MARCOS method to rank the alternatives. Table 20 expresses the extended PF normalized decision matrix which is constructed with the help of equations (19)–(22) and Table 8.

Table 21 is constructed with the help of Table 20 and equation (23).

Table 22 is constructed with the help of score function equation (3), Table 21.

TABLE 7. Initial decision matrix based on 3 decision-makers opinion.

Criteria/Alt.	M1	M2	M3	M4	M5
C1	VB, B, AB	B, B, VB	MB, B, VB	MB, MB, B	VB, VB, MB
C2	G, M, VG	MG, VVG, G	G, AG, M	VG, VG, M	MG, MG, G
C3	MG, MG, G	VG, VG, M	M, VG, VVG	AG, G, M	G, G, M
C4	VG, G, M	AG, G, M	MG, MG, G	G, VG, MG	AG, G, G
C5	M, G, VG	VG, VG, M	VVG, G, G	MG, G, VG	MG, MG, G
C6	M, G, VG	MG, VVG, G	G, AG, M	VVG, VG, M	VVG, G, MG
C7	G, MG, VG	MG, G, M	VVG, VG, G	MG, G, VG	G, M, VG
C8	M, VG, VVG	AG, G, M	G, G, M	VG, G, AG	VVG, MG, G
C9	M, G, AG	G, VG, G	MG, VG, VG	G, VG, MG	G, VG, G
C10	VG, G, M	G, VVG, MG	MG, MG, G	AG, G, M	VG, VG, MG
C11	MG, MG, G	G, VG, MG	AG, G, G	MG, G, M	VVG, VG, G
C12	VVG, G, G	MG, G, VG	M, G, VG	MG, VVG, G	G, AG, M
C13	G, VVG, MG	MG, MG, G	AG, G, M	M, VG, VVG	AG, G, M
C14	M, VG, VVG	AG, G, M	M, VG, VVG	AG, G, M	G, G, M
C15	MB, B, VB	VB, B, AB	VB, VB, MB	B, VB, AB	MB, MB, B
C16	MG, MG, G	AG, G, M	VG, VG, MG	M, G, VG	MG, VVG, G
C17	M, VG, VVG	AG, G, M	VG, G, M	AG, G, M	MG, MG, G
C18	VB, B, AB	B, VB, MB	B, B, VB	MB, B, VB	MB, MB, B
C19	MG, MG, G	G, VG, MG	AG, G, G	M, VG, VVG	AG, G, M
C20	VB, VB, MB	B, B, AB	MB, VB, VB	VB, B, AB	B, VB, MB

TABLE 8. Aggregated Pythagorean fuzzy decision matrix.

Alt./ Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
M1	0.319, 0.825	0.801, 0.379	0.769, 0.386	0.795, 0.387	0.798, 0.383	0.798, 0.383	0.811, 0.351	0.839, 0.344	0.884, 0.358	0.795, 0.387
M2	0.415, 0.74	0.825, 0.339	0.817, 0.368	0.872, 0.369	0.817, 0.368	0.825, 0.339	0.752, 0.422	0.878, 0.364	0.821, 0.342	0.824, 0.34
M3	0.464, 0.732	0.872, 0.369	0.839, 0.344	0.769, 0.386	0.841, 0.322	0.872, 0.369	0.858, 0.303	0.77, 0.408	0.829, 0.334	0.769, 0.386
M4	0.547, 0.674	0.817, 0.368	0.872, 0.369	0.805, 0.356	0.81, 0.352	0.836, 0.349	0.81, 0.352	0.915, 0.291	0.805, 0.356	0.878, 0.364
M5	0.435, 0.762	0.769, 0.386	0.77, 0.408	0.899, 0.316	0.769, 0.386	0.828, 0.336	0.801, 0.379	0.83, 0.334	0.821, 0.342	0.827, 0.336
Alt./ Criteria	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
M1	0.769, 0.386	0.841, 0.322	0.824, 0.34	0.839, 0.344	0.464, 0.732	0.769, 0.386	0.839, 0.344	0.319, 0.825	0.769, 0.386	0.435, 0.762
M2	0.805, 0.356	0.81, 0.352	0.769, 0.386	0.872, 0.369	0.319, 0.825	0.872, 0.369	0.872, 0.369	0.471, 0.726	0.805, 0.356	0.352, 0.799
M3	0.899, 0.316	0.798, 0.383	0.872, 0.369	0.839, 0.344	0.435, 0.762	0.827, 0.336	0.795, 0.387	0.415, 0.74	0.899, 0.316	0.43, 0.764
M4	0.752, 0.422	0.825, 0.339	0.839, 0.344	0.872, 0.369	0.322, 0.822	0.798, 0.383	0.878, 0.364	0.464, 0.732	0.839, 0.344	0.319, 0.825
M5	0.858, 0.303	0.872, 0.369	0.872, 0.369	0.77, 0.408	0.547, 0.674	0.825, 0.339	0.769, 0.386	0.547, 0.674	0.872, 0.369	0.471, 0.726

TABLE 9. Normalized aggregated decision matrix.

Alt./Criteria	C1	C2	C3	C4	C5	...	C18	C19	C20
M1	0.498	0.963	0.989	0.973	0.968	...	0.498	1.000	0.876
M2	0.739	0.921	0.931	0.888	0.941	...	0.822	0.948	0.699
M3	0.804	0.888	0.900	1.000	0.899	...	0.739	0.844	0.865
M4	1.000	0.941	0.878	0.948	0.941	...	0.804	0.910	0.606
M5	0.720	1.000	1.000	0.844	1.000	...	1.000	0.888	1.000

TABLE 10. Overall performance of the alternatives.

Alt.	Overall performance
M1	0.1205367
M2	0.1274976
M3	0.1101576
M4	0.1276336
M5	0.068361

TABLE 11. Performance of the alternatives by removing each criterion.

Alt./Criteria	C1	C2	C3	C4	C5	...	C18	C19	C20
M1	0.089	0.119	0.120	0.119	0.119	...	0.089	0.121	0.115
M2	0.114	0.124	0.124	0.122	0.125	...	0.119	0.125	0.112
M3	0.100	0.105	0.105	0.110	0.105	...	0.097	0.103	0.104
M4	0.128	0.125	0.122	0.125	0.125	...	0.118	0.123	0.105
M5	0.053	0.068	0.068	0.060	0.068	...	0.068	0.063	0.068

TABLE 12. Objective weight.

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
W_j^{obj}	0.133	0.025	0.027	0.032	0.022	0.021	0.038	0.047	0.014	0.027
Criteria	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
W_j^{obj}	0.044	0.020	0.035	0.040	0.163	0.027	0.031	0.120	0.037	0.096

TABLE 13. Initial direct-relation matrix based on the opinions of three decision-makers.

	C1	C2	C3	...	C18	C19	C20
C1	(0, 0, 0)	(MB, MB, B)	(B, B, VB)	...	(VB, B, AB)	(B, VB, MB)	(VB, VB, MB)
C2	(G, AG, M)	(0, 0, 0)	(VG, VG, M)	...	(AG, G, M)	(G, VG, MG)	(MG, VVG, G)
C3	(MB, MB, B)	(G, AG, M)	(0, 0, 0)	...	(MG, MG, G)	(AG, G, G)	(G, AG, M)
...	...	...	...	...	...	...	...
C18	(VB, VB, MB)	(MB, MB, B)	(VB, VB, MB)	...	(0, 0, 0)	(MB, B, VB)	(MB, MB, B)
C19	(MG, G, M)	(MG, VVG, G)	(VVG, VG, M)	...	(VG, G, M)	(0, 0, 0)	(VG, G, M)
C20	(B, VB, MB)	(B, VB, AB)	(VB, VB, MB)	...	(B, B, VB)	(MB, MB, B)	(0, 0, 0)

Ranking by PF-MARCOS method expressed in Table 23 which is evaluated with the help of equations (24), (25) and Table 22.

Based on the data presented in the Table 23, it is evident that the 4th alternative emerges as the optimal choice for the sustainable agile supplier selection process.

Again, we employed the PF-MABAC method to evaluate the alternatives ranking by the help of the same criteria weight. Here we take the help Table 8 and equation (26) to evaluate an PF normalized decision matrix, which is expressed in Table 24.

Table 25 is evaluated with the help of equation (27) and Table 24.

Table 14. Aggregated direct influence matrix.

	C1		C2		C3		C4		C5		C6		C7	
C1	0	0	0.547	0.674	0.415	0.74	0.464	0.732	0.435	0.762	0.471	0.726	0.322	0.822
C2	0.872	0.369	0	0	0.817	0.368	0.872	0.369	0.817	0.368	0.825	0.339	0.752	0.422
C3	0.547	0.674	0.872	0.369	0	0	0.769	0.386	0.841	0.322	0.872	0.369	0.858	0.303
C4	0.795	0.387	0.817	0.368	0.872	0.369	0	0	0.81	0.352	0.836	0.349	0.81	0.352
C5	0.752	0.422	0.769	0.386	0.77	0.408	0.899	0.316	0	0	0.828	0.336	0.801	0.379
C6	0.77	0.408	0.798	0.383	0.798	0.383	0.884	0.358	0.841	0.322	0	0	0.752	0.422
C7	0.81	0.352	0.825	0.339	0.825	0.339	0.821	0.342	0.81	0.352	0.824	0.34	0	0
C8	0.752	0.422	0.872	0.369	0.872	0.369	0.829	0.334	0.798	0.383	0.769	0.386	0.839	0.344
C9	0.547	0.674	0.836	0.349	0.836	0.349	0.805	0.356	0.825	0.339	0.872	0.369	0.878	0.364
C10	0.769	0.386	0.828	0.336	0.828	0.336	0.821	0.342	0.872	0.369	0.839	0.344	0.77	0.408
C11	0.752	0.422	0.839	0.344	0.798	0.383	0.839	0.344	0.824	0.34	0.872	0.369	0.915	0.291
C12	0.795	0.387	0.878	0.364	0.817	0.368	0.878	0.364	0.769	0.386	0.795	0.387	0.83	0.334
C13	0.77	0.408	0.77	0.408	0.841	0.322	0.77	0.408	0.872	0.369	0.824	0.34	0.811	0.351
C14	0.769	0.386	0.915	0.291	0.81	0.352	0.915	0.291	0.839	0.344	0.769	0.386	0.752	0.422
C15	0.435	0.762	0.464	0.732	0.435	0.762	0.471	0.726	0.322	0.822	0.435	0.762	0.547	0.674
C16	0.798	0.383	0.795	0.387	0.798	0.383	0.811	0.351	0.811	0.351	0.827	0.336	0.81	0.352
C17	0.769	0.386	0.872	0.369	0.825	0.339	0.752	0.422	0.752	0.422	0.839	0.344	0.801	0.379
C18	0.435	0.762	0.547	0.674	0.435	0.762	0.547	0.674	0.464	0.732	0.547	0.674	0.547	0.674
C19	0.752	0.422	0.825	0.339	0.836	0.349	0.81	0.352	0.81	0.352	0.77	0.408	0.821	0.342
C20	0.471	0.726	0.322	0.822	0.435	0.762	0.547	0.674	0.435	0.762	0.547	0.674	0.464	0.732

	C8		C9		C10		C11		C12		C13		C14	
C1	0.435	0.762	0.547	0.674	0.435	0.762	0.547	0.674	0.464	0.732	0.547	0.674	0.435	0.762
C2	0.878	0.364	0.825	0.339	0.824	0.34	0.805	0.356	0.81	0.352	0.872	0.369	0.795	0.387
C3	0.77	0.408	0.872	0.369	0.769	0.386	0.899	0.316	0.798	0.383	0.795	0.387	0.824	0.34
C4	0.915	0.291	0.836	0.349	0.878	0.364	0.752	0.422	0.825	0.339	0.878	0.364	0.769	0.386
C5	0.83	0.334	0.828	0.336	0.827	0.336	0.858	0.303	0.872	0.369	0.769	0.386	0.77	0.408
C6	0.878	0.364	0.769	0.386	0.752	0.422	0.795	0.387	0.899	0.316	0.872	0.369	0.839	0.344
C7	0.77	0.408	0.878	0.364	0.858	0.303	0.824	0.34	0.752	0.422	0.839	0.344	0.872	0.369
C8	0	0	0.827	0.336	0.795	0.387	0.769	0.386	0.858	0.303	0.872	0.369	0.795	0.387
C9	0.872	0.369	0	0	0.824	0.34	0.878	0.364	0.795	0.387	0.77	0.408	0.878	0.364
C10	0.839	0.344	0.798	0.383	0	0	0.795	0.387	0.824	0.34	0.839	0.344	0.769	0.386
C11	0.872	0.369	0.878	0.364	0.872	0.369	0	0	0.769	0.386	0.872	0.369	0.805	0.356
C12	0.795	0.387	0.769	0.386	0.839	0.344	0.839	0.344	0	0	0.795	0.387	0.899	0.316
C13	0.824	0.34	0.798	0.383	0.872	0.369	0.872	0.369	0.872	0.369	0	0	0.839	0.344
C14	0.769	0.386	0.825	0.339	0.77	0.408	0.795	0.387	0.839	0.344	0.872	0.369	0	0
C15	0.435	0.762	0.547	0.674	0.435	0.762	0.547	0.674	0.464	0.732	0.547	0.674	0.415	0.74
C16	0.827	0.336	0.824	0.34	0.872	0.369	0.769	0.386	0.77	0.408	0.872	0.369	0.798	0.383
C17	0.795	0.387	0.769	0.386	0.795	0.387	0.878	0.364	0.839	0.344	0.77	0.408	0.825	0.339
C18	0.415	0.74	0.464	0.732	0.435	0.762	0.471	0.726	0.322	0.822	0.435	0.762	0.547	0.674
C19	0.769	0.386	0.769	0.386	0.769	0.386	0.839	0.344	0.795	0.387	0.872	0.369	0.836	0.349
C20	0.547	0.674	0.415	0.74	0.464	0.732	0.435	0.762	0.471	0.726	0.319	0.825	0.435	0.762

	C15		C16		C17		C18		C19		C20	
C1	0.464	0.732	0.547	0.674	0.435	0.762	0.319	0.825	0.471	0.726	0.435	0.762
C2	0.752	0.422	0.798	0.383	0.872	0.369	0.878	0.364	0.805	0.356	0.825	0.339
C3	0.795	0.387	0.825	0.339	0.795	0.387	0.769	0.386	0.899	0.316	0.872	0.369
C4	0.77	0.408	0.872	0.369	0.878	0.364	0.798	0.383	0.839	0.344	0.899	0.316
C5	0.769	0.386	0.836	0.349	0.769	0.386	0.825	0.339	0.872	0.369	0.752	0.422
C6	0.878	0.364	0.828	0.336	0.798	0.383	0.872	0.369	0.795	0.387	0.858	0.303
C7	0.769	0.386	0.839	0.344	0.825	0.339	0.872	0.369	0.824	0.34	0.795	0.387
C8	0.798	0.383	0.769	0.386	0.872	0.369	0.77	0.408	0.769	0.386	0.824	0.34
C9	0.825	0.339	0.805	0.356	0.824	0.34	0.839	0.344	0.878	0.364	0.769	0.386
C10	0.872	0.369	0.899	0.316	0.769	0.386	0.872	0.369	0.827	0.336	0.839	0.344
C11	0.872	0.369	0.839	0.344	0.872	0.369	0.77	0.408	0.839	0.344	0.878	0.364
C12	0.77	0.408	0.872	0.369	0.839	0.344	0.915	0.291	0.878	0.364	0.77	0.408
C13	0.839	0.344	0.795	0.387	0.872	0.369	0.83	0.334	0.77	0.408	0.915	0.291
C14	0.872	0.369	0.878	0.364	0.811	0.351	0.878	0.364	0.915	0.291	0.83	0.334
C15	0	0	0.435	0.762	0.547	0.674	0.435	0.762	0.547	0.674	0.415	0.74
C16	0.752	0.422	0	0	0.858	0.303	0.899	0.316	0.769	0.386	0.83	0.334
C17	0.858	0.303	0.839	0.344	0	0	0.752	0.422	0.798	0.383	0.878	0.364
C18	0.435	0.762	0.547	0.674	0.435	0.762	0	0	0.464	0.732	0.547	0.674
C19	0.824	0.34	0.795	0.387	0.878	0.364	0.795	0.387	0	0	0.795	0.387
C20	0.435	0.762	0.43	0.764	0.319	0.825	0.415	0.74	0.547	0.674	0	0

Table 15. Aggregated normalized direct-relation matrix.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
C1	0.50	0.42	0.31	0.34	0.30	0.35	0.21	0.30	0.42	0.30	0.42	0.34	0.42	0.30	0.34	0.42	0.30	0.21	0.35	0.30
C2	0.81	0.50	0.77	0.81	0.77	0.78	0.69	0.82	0.78	0.78	0.76	0.77	0.81	0.74	0.69	0.75	0.81	0.82	0.76	0.78
C3	0.42	0.81	0.50	0.72	0.80	0.81	0.82	0.71	0.81	0.72	0.85	0.75	0.74	0.78	0.74	0.78	0.74	0.72	0.85	0.81
C4	0.74	0.77	0.81	0.50	0.77	0.79	0.77	0.88	0.79	0.82	0.69	0.78	0.82	0.72	0.71	0.81	0.82	0.75	0.79	0.85
C5	0.69	0.72	0.71	0.85	0.50	0.79	0.75	0.79	0.79	0.79	0.82	0.81	0.72	0.71	0.72	0.79	0.72	0.78	0.81	0.69
C6	0.71	0.75	0.75	0.83	0.80	0.50	0.69	0.82	0.72	0.69	0.74	0.85	0.81	0.79	0.82	0.79	0.75	0.81	0.74	0.82
C7	0.77	0.78	0.78	0.78	0.77	0.78	0.50	0.71	0.82	0.82	0.78	0.69	0.79	0.81	0.72	0.79	0.78	0.81	0.78	0.74
C8	0.69	0.81	0.81	0.79	0.75	0.72	0.79	0.50	0.79	0.74	0.72	0.82	0.81	0.74	0.75	0.72	0.81	0.71	0.72	0.78
C9	0.42	0.79	0.79	0.76	0.78	0.81	0.82	0.81	0.50	0.78	0.82	0.74	0.71	0.82	0.78	0.76	0.78	0.79	0.82	0.72
C10	0.72	0.79	0.79	0.78	0.81	0.79	0.71	0.79	0.75	0.50	0.74	0.78	0.79	0.72	0.81	0.85	0.72	0.81	0.79	0.79
C11	0.69	0.79	0.75	0.79	0.78	0.81	0.88	0.81	0.82	0.81	0.50	0.72	0.81	0.76	0.81	0.79	0.81	0.71	0.79	0.82
C12	0.74	0.82	0.77	0.82	0.72	0.74	0.79	0.74	0.72	0.79	0.79	0.50	0.74	0.85	0.71	0.81	0.79	0.88	0.82	0.71
C13	0.71	0.71	0.80	0.71	0.81	0.78	0.77	0.78	0.75	0.81	0.81	0.81	0.50	0.79	0.79	0.74	0.81	0.79	0.71	0.88
C14	0.72	0.88	0.77	0.88	0.79	0.72	0.69	0.72	0.78	0.71	0.74	0.79	0.81	0.50	0.81	0.82	0.77	0.82	0.88	0.79
C15	0.30	0.34	0.30	0.35	0.21	0.30	0.42	0.30	0.42	0.30	0.42	0.34	0.42	0.31	0.50	0.30	0.42	0.30	0.42	0.31
C16	0.75	0.74	0.75	0.77	0.77	0.79	0.77	0.79	0.78	0.81	0.72	0.71	0.81	0.75	0.69	0.50	0.82	0.85	0.72	0.79
C17	0.72	0.81	0.78	0.69	0.69	0.79	0.75	0.74	0.72	0.74	0.82	0.79	0.71	0.78	0.82	0.79	0.50	0.69	0.75	0.82
C18	0.30	0.42	0.30	0.42	0.34	0.42	0.42	0.31	0.34	0.30	0.35	0.21	0.30	0.42	0.30	0.42	0.30	0.50	0.34	0.42
C19	0.69	0.78	0.79	0.77	0.77	0.71	0.78	0.72	0.72	0.72	0.79	0.74	0.81	0.79	0.78	0.74	0.82	0.74	0.50	0.74
C20	0.35	0.21	0.30	0.42	0.30	0.42	0.34	0.42	0.31	0.34	0.30	0.35	0.21	0.30	0.30	0.30	0.21	0.31	0.42	0.50

Table 16. Total influence matrix T.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
C1	0.1740	0.1822	0.1718	0.1785	0.1703	0.1773	0.1660	0.1731	0.1810	0.1710	0.1818	0.1734	0.1816	0.1721	0.1769	0.1827	0.1733	0.1707	0.1788	0.1799
C2	0.3637	0.3734	0.3826	0.3966	0.3804	0.3911	0.3792	0.3899	0.3885	0.3829	0.3889	0.3821	0.3914	0.3831	0.3853	0.3900	0.3897	0.3985	0.3929	0.4031
C3	0.3369	0.3911	0.3639	0.3891	0.3809	0.3909	0.3856	0.3814	0.3883	0.3774	0.3928	0.3789	0.3850	0.3838	0.3864	0.3905	0.3835	0.3905	0.3970	0.4028
C4	0.3634	0.3949	0.3901	0.3815	0.3849	0.3960	0.3884	0.3981	0.3934	0.3898	0.3894	0.3879	0.3964	0.3864	0.3912	0.3989	0.3948	0.3985	0.3997	0.4123
C5	0.3533	0.3844	0.3763	0.3961	0.3605	0.3880	0.3797	0.3849	0.3856	0.3802	0.3896	0.3819	0.3827	0.3783	0.3839	0.3896	0.3811	0.3932	0.3930	0.3940
C6	0.3561	0.3875	0.3798	0.3961	0.3811	0.3715	0.3779	0.3884	0.3831	0.3760	0.3862	0.3862	0.3899	0.3849	0.3918	0.3911	0.3842	0.3966	0.3903	0.4039
C7	0.3619	0.3928	0.3851	0.3958	0.3818	0.3922	0.3682	0.3846	0.3920	0.3868	0.3916	0.3789	0.3915	0.3889	0.3884	0.3944	0.3894	0.3995	0.3957	0.4017
C8	0.3530	0.3897	0.3822	0.3916	0.3757	0.3837	0.3821	0.3662	0.3852	0.3771	0.3831	0.3823	0.3879	0.3798	0.3851	0.3851	0.3864	0.3883	0.3871	0.3993
C9	0.3392	0.3922	0.3846	0.3940	0.3821	0.3933	0.3878	0.3899	0.3709	0.3835	0.3930	0.3811	0.3857	0.3885	0.3916	0.3914	0.3885	0.3976	0.3972	0.3995
C10	0.3582	0.3918	0.3841	0.3948	0.3835	0.3918	0.3808	0.3885	0.3864	0.3653	0.3879	0.3834	0.3905	0.3821	0.3931	0.3971	0.3844	0.3984	0.3948	0.4038
C11	0.3628	0.3992	0.3885	0.4028	0.3885	0.4001	0.3979	0.3967	0.3980	0.3920	0.3796	0.3865	0.3987	0.3915	0.4002	0.4003	0.3971	0.3992	0.4024	0.4128
C12	0.3613	0.3960	0.3848	0.3994	0.3798	0.3906	0.3874	0.3872	0.3868	0.3858	0.3931	0.3673	0.3893	0.3924	0.3887	0.3966	0.3909	0.4045	0.3989	0.4008
C13	0.3581	0.3878	0.3856	0.3913	0.3840	0.3917	0.3847	0.3883	0.3869	0.3856	0.3929	0.3858	0.3723	0.3871	0.3925	0.3906	0.3905	0.3974	0.3909	0.4097
C14	0.3616	0.4012	0.3866	0.4047	0.3860	0.3911	0.3833	0.3878	0.3926	0.3826	0.3917	0.3877	0.3954	0.3717	0.3968	0.3987	0.3911	0.4027	0.4043	0.4075
C15	0.1637	0.1797	0.1740	0.1817	0.1671	0.1772	0.1821	0.1757	0.1837	0.1737	0.1846	0.1759	0.1842	0.1754	0.1901	0.1779	0.1836	0.1796	0.1864	0.1833
C16	0.3564	0.3854	0.3781	0.3905	0.3773	0.3879	0.3805	0.3845	0.3851	0.3816	0.3831	0.3756	0.3880	0.3801	0.3820	0.3712	0.3871	0.3975	0.3872	0.4000
C17	0.3522	0.3868	0.3776	0.3829	0.3697	0.3853	0.3766	0.3787	0.3784	0.3743	0.3863	0.3777	0.3790	0.3796	0.3873	0.3867	0.3638	0.3842	0.3857	0.3987
C18	0.1658	0.1871	0.1760	0.1888	0.1773	0.1870	0.1840	0.1784	0.1805	0.1757	0.1817	0.1699	0.1788	0.1845	0.1793	0.1876	0.1780	0.1946	0.1833	0.1927
C19	0.3512	0.3860	0.3787	0.3882	0.3751	0.3812	0.3793	0.3783	0.3792	0.3739	0.3855	0.3753	0.3860	0.3807	0.3855	0.3843	0.3849	0.3881	0.3710	0.3947
C20	0.1571	0.1612	0.1637	0.1761	0.1627	0.1743	0.1664	0.1730	0.1662	0.1656	0.1664	0.1663	0.1603	0.1645	0.1668	0.1672	0.1595	0.1695	0.1759	0.1847

The BAA matrix represent in Table 26, which is evaluated with the help of Table 25 and equations (28)–(30). Table 27 constructed with the help of equations (31)–(33) and Tables 25, 26.

Table 28 express the alternatives ranking by PF-MABAC method, which is constructed by the help of Table 27 and equation (34).

From Tables 23 and 28, it is evident that the 4th alternative consistently emerges as the optimal choice when evaluated using both the integrated PF-MEREC-DEMATEL-MARCOS and PF-MEREC-DEMATEL-MABAC methods. This consistency in ranking highlights the robustness and reliability of these integrated methodologies in identifying the best alternative, reinforcing their applicability in solving complex decision-making problems.

5. Sensitivity analysis

Sensitivity analysis is a key tool for ranking alternatives, especially in multi-criteria decision-making. It enables decision-makers to assess how robust the ranking outcomes are in response to changes or uncertainties

TABLE 17. Prominence and relation matrix.

Criteria	Row sum (R_i)	Column sum (C_i)	Prominence ($R_i + C_i$)	Relation ($R_i - C_i$)	Influence group
C1	3.5164	6.350114165	9.8666	−2.8337	Effect
C2	7.7332	6.950256645	14.6834	0.7829	Cause
C3	7.6768	6.793776258	14.4706	0.8830	Cause
C4	7.8359	7.020339237	14.8563	0.8156	Cause
C5	7.6563	6.748580813	14.4048	0.9077	Cause
C6	7.7025	6.942135471	14.6446	0.7603	Cause
C7	7.7610	6.817867548	14.5788	0.9431	Cause
C8	7.6511	6.873485242	14.5246	0.7776	Cause
C9	7.7315	6.891815858	14.6233	0.8397	Cause
C10	7.7407	6.780936646	14.5216	0.9598	Cause
C11	7.8949	6.929194039	14.8241	0.9657	Cause
C12	7.7817	6.78419125	14.5659	0.9975	Cause
C13	7.7539	6.914531922	14.6684	0.8394	Cause
C14	7.8250	6.8356435	14.6607	0.9894	Cause
C15	3.5793	6.942754528	10.5221	−3.3634	Effect
C16	7.6589	6.971731773	14.6307	0.6872	Cause
C17	7.5913	6.881901249	14.4732	0.7094	Cause
C18	3.6310	7.049008835	10.6801	−3.4180	Effect
C19	7.6073	7.012494193	14.6198	0.5948	Cause
C20	3.3473	7.185372448	10.5327	−3.8380	Effect

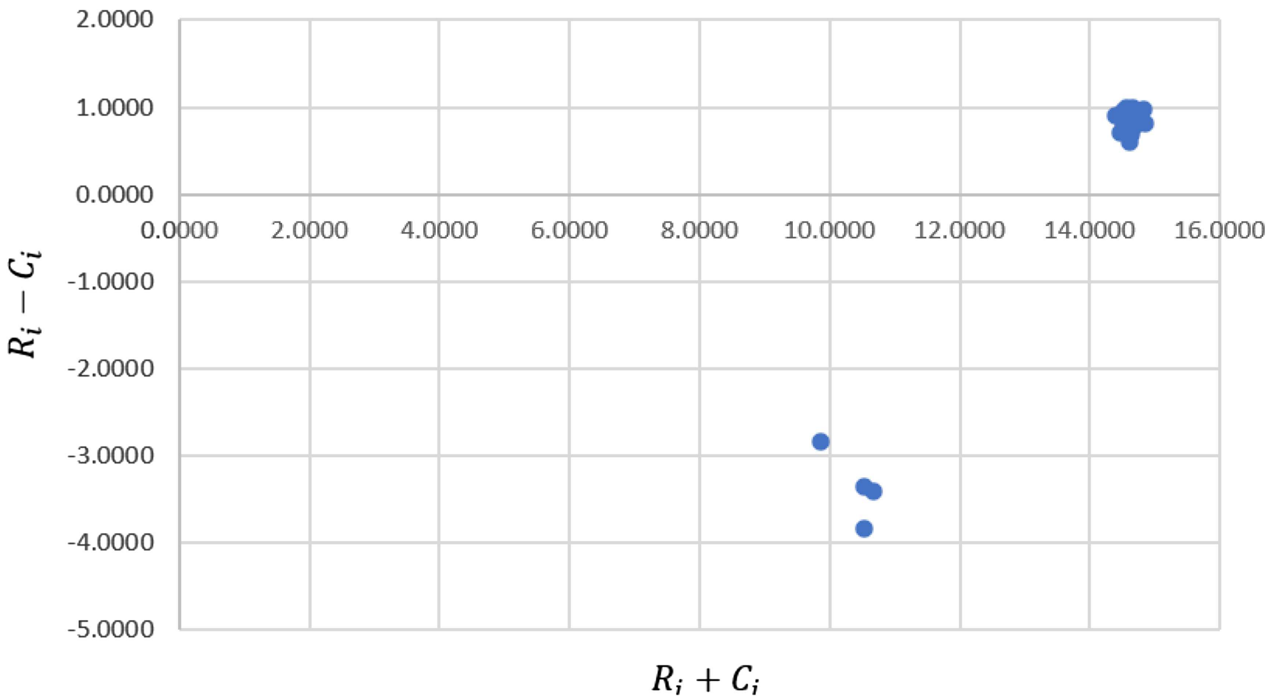

FIGURE 2. Network relations map.

TABLE 18. Subjective criteria weight.

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
W_J^{sub}	0.03694	0.05292	0.05217	0.05354	0.05194	0.05277	0.05257	0.05234	0.05271	0.05237
Criteria	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
W_J^{sub}	0.05346	0.05254	0.05287	0.05288	0.03975	0.05271	0.05215	0.04035	0.05266	0.04034

TABLE 19. Final criteria weight.

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Criteria weight(W_j)	0.1071	0.0291	0.0305	0.0371	0.0248	0.0244	0.0437	0.0534	0.0161	0.0312
Criteria	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
Criteria weight(W_j)	0.0512	0.0235	0.0408	0.0458	0.1416	0.0315	0.0352	0.1057	0.0429	0.0845

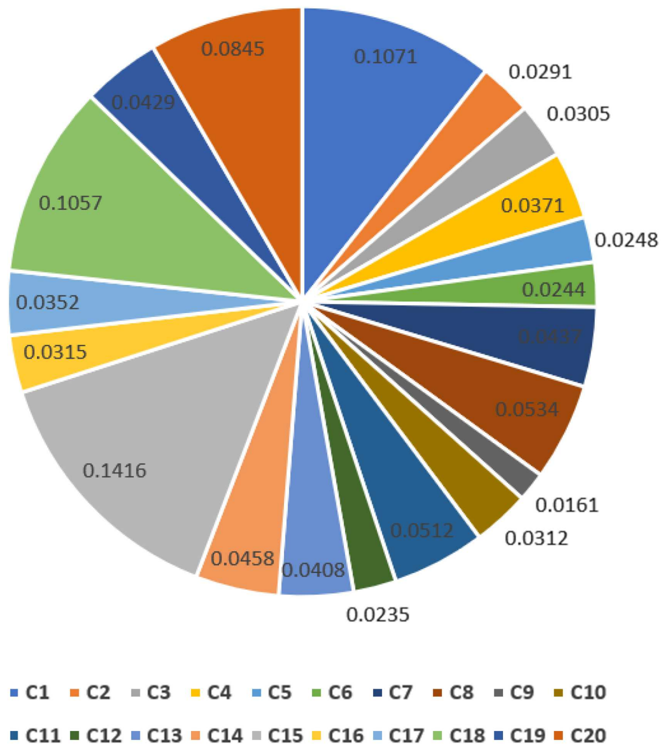

FIGURE 3. Criteria weights.

in the input parameters. Triantaphyllou and Sanchez, in their article, discuss the sensitivity analysis of MCDM methods [47]. The results of sensitivity analysis demonstrate how variations in these parameters affect the outcome of a model decision. After normalization, the values for each alternative are as follows: $M1 = 0.2020$, $M2 = 0.2056$, $M3 = 0.2004$, $M4 = 0.2064$, and $M5 = 0.1856$, these values are treated as the weights of each alternative. Table 29 below shows the values for each phase of the sensitivity analysis. It is also noted that from

Table 20. Extended PF normalized decision matrix.

Alt./ Criteria	C1		C2		C3		C4		C5		C6		C7	
M1	0.825	0.319	0.801	0.379	0.769	0.386	0.795	0.387	0.798	0.383	0.798	0.383	0.811	0.351
M2	0.74	0.415	0.825	0.339	0.817	0.368	0.872	0.369	0.817	0.368	0.825	0.339	0.752	0.422
M3	0.732	0.464	0.872	0.369	0.839	0.344	0.769	0.386	0.841	0.322	0.872	0.369	0.858	0.303
M4	0.674	0.547	0.817	0.368	0.872	0.369	0.805	0.356	0.81	0.352	0.836	0.349	0.81	0.352
M5	0.762	0.435	0.769	0.386	0.77	0.408	0.899	0.316	0.769	0.386	0.828	0.336	0.801	0.379
Xeej	0.674	0.547	0.872	0.339	0.872	0.344	0.899	0.316	0.841	0.322	0.872	0.339	0.858	0.303
Xej	0.825	0.319	0.769	0.386	0.769	0.408	0.769	0.387	0.769	0.386	0.798	0.383	0.752	0.422

Alt./ Criteria	C8		C9		C10		C11		C12		C13		C14	
M1	0.839	0.344	0.884	0.358	0.795	0.387	0.769	0.386	0.841	0.322	0.824	0.34	0.839	0.344
M2	0.878	0.364	0.821	0.342	0.824	0.34	0.805	0.356	0.81	0.352	0.769	0.386	0.872	0.369
M3	0.77	0.408	0.829	0.334	0.769	0.386	0.899	0.316	0.798	0.383	0.872	0.369	0.839	0.344
M4	0.915	0.291	0.805	0.356	0.878	0.364	0.752	0.422	0.825	0.339	0.839	0.344	0.872	0.369
M5	0.83	0.334	0.821	0.342	0.827	0.336	0.858	0.303	0.872	0.369	0.872	0.369	0.77	0.408
Xeej	0.915	0.291	0.884	0.334	0.878	0.336	0.899	0.303	0.872	0.322	0.872	0.34	0.872	0.344
Xej	0.77	0.408	0.805	0.358	0.769	0.387	0.752	0.422	0.798	0.383	0.769	0.386	0.77	0.408

Alt./ Criteria	C15		C16		C17		C18		C19		C20	
M1	0.732	0.464	0.769	0.386	0.839	0.344	0.825	0.319	0.769	0.386	0.762	0.435
M2	0.825	0.319	0.872	0.369	0.872	0.369	0.726	0.471	0.805	0.356	0.799	0.352
M3	0.762	0.435	0.827	0.336	0.795	0.387	0.74	0.415	0.899	0.316	0.764	0.43
M4	0.822	0.322	0.798	0.383	0.878	0.364	0.732	0.464	0.839	0.344	0.825	0.319
M5	0.674	0.547	0.825	0.339	0.769	0.386	0.674	0.547	0.872	0.369	0.726	0.471
Xeej	0.674	0.547	0.872	0.339	0.878	0.344	0.674	0.547	0.899	0.316	0.726	0.471
Xej	0.825	0.319	0.769	0.386	0.769	0.387	0.825	0.319	0.769	0.386	0.825	0.319

Table 21. PF weighted normalized decision matrix.

Alt./ Criteria	C1		C2		C3		C4		...	C19		C20	
M1	0.339	0.885	0.172	0.972	0.164	0.971	0.191	0.965	...	0.194	0.960	0.266	0.932
M2	0.285	0.910	0.181	0.969	0.182	0.970	0.227	0.964	...	0.209	0.957	0.287	0.916
M3	0.281	0.921	0.202	0.971	0.191	0.968	0.181	0.965	...	0.262	0.952	0.267	0.931
M4	0.251	0.937	0.178	0.971	0.207	0.970	0.195	0.962	...	0.226	0.955	0.303	0.908
M5	0.298	0.915	0.160	0.973	0.164	0.973	0.244	0.958	...	0.244	0.958	0.248	0.938
Veej	0.339	0.937	0.202	0.973	0.207	0.973	0.244	0.965	...	0.262	0.960	0.303	0.938
Vej	0.251	0.885	0.160	0.969	0.164	0.968	0.181	0.958	...	0.194	0.952	0.248	0.908

Table 22. PF weighted normalized crisp decision matrix.

Alt./ Criteria	C1	C2	C3	C4	C5	C6	C7	...	C19	C20
M1	0.1660	0.0422	0.0417	0.0522	0.0356	0.0351	0.0666	...	0.0581	0.1010
M2	0.1265	0.0469	0.0461	0.0615	0.0376	0.0398	0.0542	...	0.0644	0.1220
M3	0.1152	0.0486	0.0497	0.0504	0.0423	0.0409	0.0778	...	0.0813	0.1021
M4	0.0920	0.0440	0.0508	0.0559	0.0383	0.0395	0.0664	...	0.0692	0.1337
M5	0.1260	0.0398	0.0401	0.0707	0.0340	0.0398	0.0626	...	0.0708	0.0904
Veej	0.1181	0.0473	0.0479	0.0637	0.0380	0.0400	0.0646	...	0.0735	0.1057
Vej	0.1399	0.0434	0.0450	0.0573	0.0383	0.0383	0.0674	...	0.0659	0.1184

TABLE 23. Utility degree and utility function of each alternative.

Alternative	S_i	k_i^+	k_i^-	$F(k_i)$	Rank
M1	1.4171	1.0073	0.9904	0.6658	3
M2	1.4422	1.0251	1.0080	0.6776	2
M3	1.4062	0.9995	0.9828	0.6607	4
M4	1.4476	1.0290	1.0118	0.6802	1
M5	1.3024	0.9257	0.9103	0.6119	5

TABLE 24. PF normalized decision matrix.

Alt./ Criteria	C1		C2		C3		C4		...	C19		C20	
M1	0.825	0.319	0.801	0.379	0.769	0.386	0.795	0.387	...	0.769	0.386	0.762	0.435
M2	0.74	0.415	0.825	0.339	0.817	0.368	0.872	0.369	...	0.805	0.356	0.799	0.352
M3	0.732	0.464	0.872	0.369	0.839	0.344	0.769	0.386	...	0.899	0.316	0.764	0.43
M4	0.674	0.547	0.817	0.368	0.872	0.369	0.805	0.356	...	0.839	0.344	0.825	0.319
M5	0.762	0.435	0.769	0.386	0.77	0.408	0.899	0.316	...	0.872	0.369	0.726	0.471

TABLE 25. PF weighted normalized decision matrix.

Alt./ Criteria	C1		C2		C3		C4		...	C19		C20	
M1	0.339	0.885	0.172	0.972	0.164	0.971	0.191	0.965	...	0.194	0.960	0.266	0.932
M2	0.285	0.910	0.181	0.969	0.182	0.970	0.227	0.964	...	0.209	0.957	0.287	0.916
M3	0.281	0.921	0.202	0.971	0.191	0.968	0.181	0.965	...	0.262	0.952	0.267	0.931
M4	0.251	0.937	0.178	0.971	0.207	0.970	0.195	0.962	...	0.226	0.955	0.303	0.908
M5	0.298	0.915	0.160	0.973	0.164	0.973	0.244	0.958	...	0.244	0.958	0.248	0.938

TABLE 26. BAA matrix.

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
0.289, 0.915	0.178, 0.971	0.181, 0.971	0.206, 0.963	0.161, 0.975	0.168, 0.975	0.212, 0.956	0.257, 0.945	0.137, 0.983	0.185, 0.969
C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
0.235, 0.949	0.164, 0.976	0.219, 0.959	0.233, 0.955	0.341, 0.884	0.186, 0.968	0.202, 0.966	0.284, 0.918	0.226, 0.956	0.273, 0.926

TABLE 27. Distance of alternatives from the Border Approximation Area matrix.

Alt/Criteria	C1	C2	C3	C4	C5	...	C18	C19	C20
M1	0.0431	−0.0019	−0.0037	−0.0053	−0.0018	...	0.045295	−0.0100	−0.0078
M2	0.0036	0.0028	0.0007	0.0040	0.0002	...	−0.0072	−0.0037	0.0133
M3	−0.0076	0.0045	0.0043	−0.0071	0.0049	...	0.00622	0.0132	−0.0066
M4	−0.0309	0.0000	0.0054	−0.0016	0.0008	...	−0.00494	0.0011	0.0250
M5	0.0032	−0.0043	−0.0053	0.0132	−0.0034	...	−0.02795	0.0027	−0.0184

Table 28. Ranking table.

Alt.	F_i value	Rank
M1	0.0304	3
M2	0.0555	2
M3	0.0195	4
M4	0.0609	1
M5	−0.0843	5

Table 29. Sensitivity analysis matrix.

Alt.	Original	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4
M1	0.2020	0.2418	0.2291	0.2163	0.2036	0.1909	0.1782	0.1654	0.1527
M2	0.2056	0.2461	0.2331	0.2202	0.2072	0.1943	0.1813	0.1684	0.1554
M3	0.2004	0.2399	0.2273	0.2147	0.2020	0.1894	0.1768	0.1642	0.1515
M4	0.2064	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4
M5	0.1856	0.2222	0.2105	0.1988	0.1871	0.1754	0.1637	0.1520	0.1403
Total	1	1	1	1	1	1	1	1	1

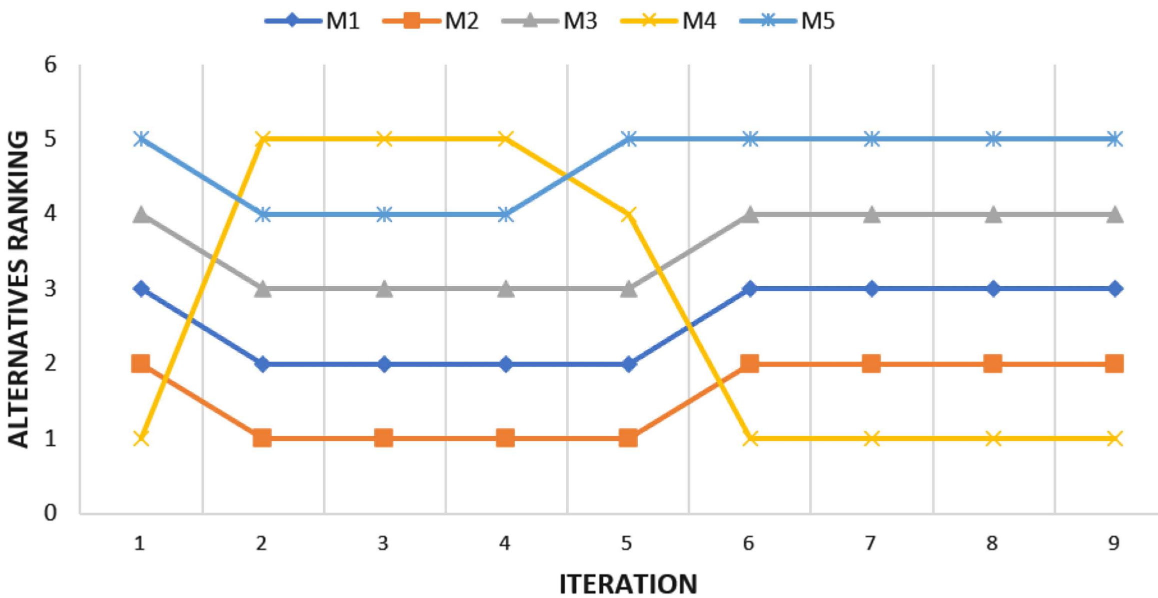

Figure 4. Graphical representation of sensitivity analysis.

the 6th iteration onward, with a value of 0.25, the ranking order of the alternatives becomes stable. Additionally, Table 29 shows that from the 6th iteration onward, the 4th alternative consistently holds the top position.

From the above Table 29 and Figures 4, 5, it is clearly observed that from the 6th iteration onwards, the 4th alternative consistently maintains its top position without any changes. This illustrates the sensitivity analysis of the ranking derived from the first integrated MCDM model, evaluated using the PF-MEREC-DEMATEL-MARCOS method, with the ranking results shown in Table 23. Similarly, by following the same procedure, a

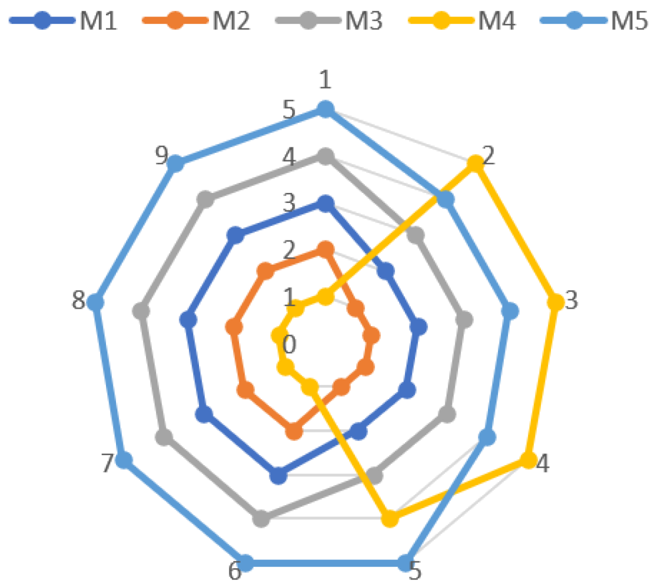

FIGURE 5. Radar diagram of sensitivity analysis.

TABLE 30. Comparision analysis matrix.

Alternative	PF-MEREC-DEMATEL-MARCOS score	Rank	PF-MEREC-DEMATEL-MABAC score	Rank
M1	0.6658	3	0.0304	3
M2	0.6776	2	0.0555	2
M3	0.6607	4	0.0195	4
M4	0.6802	1	0.0609	1
M5	0.6119	5	−0.0843	5

sensitivity analysis can be performed for the integrated PF-MEREC-DEMATEL-MABAC method, with the help of ranking results provided in Table 28.

5.1. Comparision analysis

Table 30 below represents the comparison analysis of PF-MEREC-DEMATEL-MARCOS and PF-MEREC-DEMATEL-MABAC methods.

From Table 30, it is evident that both the integrated MCDM methods indicate the 4th alternative as the optimal choice for the sustainable agile supplier selection process. The consistency observed across both methods indicates strong reliability in their evaluations, affirming that the 4th alternative best fulfills the necessary criteria for sustainability and agility compared to other options. This alignment reinforces the recommendation, showing that the 4th alternative effectively balances essential factors to support long-term goals in supplier selection.

6. Managerial implications

This study underscores the importance of adopting sustainable agile supplier selection practices in supply chain management. Some of the important implications are expressed below.

- **Improved Competitive Edge through Sustainability:** By choosing suppliers based on sustainability standards, organizations can boost their competitiveness, meet increasing environmental expectations, and attract environmentally aware customers.
- **Supply Chain Resilience and Agility:**
  Incorporating agility in supplier selection helps companies swiftly adjust to market shifts, ensuring consistent supply chain operations even in times of disruption.
- **Comprehensive Decision-Making with hybrid MCDM Models:**
  The application of hybrid Multi-Criteria Decision-Making (MCDM) models enables managers to assess suppliers holistically, factoring in both quantitative and qualitative elements for more informed decisions.
- **Strengthened Supplier Partnerships through Long-Term Collaboration:**
  Focusing on sustainability in supplier selection cultivates long-lasting, mutually beneficial relationships, which enhances supply chain stability and supports sustainability goals.
- **Adaptive Decision-Making with Sensitivity Analysis:**
  Sensitivity analysis allows managers to understand the impact of changes in criteria weights on supplier rankings, facilitating adjustments to supplier selection strategies based on evolving market conditions.

Adopting sustainable agile supplier selection can significantly improve both supply chain resilience and efficiency, while aligning with broader sustainability goals. In today's rapidly evolving business environment, this approach helps companies enhance their competitiveness and long-term success by enabling them to collaborate with suppliers who best meet the criteria outlined in the selection framework. This not only strengthens supplier relationships but also ensures that the business remains adaptable to market changes, fostering a more robust and sustainable supply chain.

7. Conclusion

From Tables 23 and 28, it is evident that the 4th supplier is the optimal alternative for a sustainable agile supplier selection process. Effective supplier selection is crucial for companies striving to enhance supply chain efficiency through a sustainable and agile approach. This study seeks to identify the critical components of an agile and sustainable framework required to select the most suitable supplier for sustainable agile manufacturing processes. To address this challenge, the study employed an integrated Multi-Criteria Decision Making (MCDM) framework to handle the complexities of supplier selection. Incorporating inputs from three decision-makers, the study evaluates 20 criteria across five alternatives. Complementary MCDM methods, such as PF-MEREC and PF-DEMATEL, are utilized to determine objective and subjective criteria weights, respectively. The integration of these weights ensures a more precise calculation of the final criteria weights, enhancing the reliability and accuracy of the analysis. In addition, this article utilized two different Multi-Criteria Decision-Making (MCDM) methods, namely PF-MARCOS and PF-MABAC, to determine the optimal ranking of alternatives. Both of these integrated MCDM models identified the 4th alternative as the optimal choice. Additionally, our research examines the interdependencies among the 20 criteria and includes sensitivity and comparison analyses to strengthen the robustness of our research. Sensitivity analysis enhances the credibility of our results by testing their stability, while comparison analysis further verifies data reliability and consistency. Our results illustrate the effectiveness of integrated MCDM methods in supplier selection, allowing companies to align their processes with sustainability goals, respond to dynamic market demands, and drive innovation within the supply chain. By adopting these methodologies, organizations can foster sustainable and agile supply chain management practices, thus strengthening their competitive position in the industrial sector.

The limitations of this paper are as follows. Firstly, this study includes only a small number of decision-makers, which may limit the generalizability of the insights. Secondly, this article uses 20 criteria to identify the best supplier, expanding these criteria could potentially yield more accurate results. Lastly, the complexity of this integrated method may present challenges when applying it to real-world problems. Since our methodology is entirely based on the decision maker's judgments, the ranking of alternatives is not fixed and can vary according to each decision maker's perspective.

Future research projects will address the limitations of this work by developing new integrated models under various fuzzy environments, such as picture fuzzy sets, trapezoidal fuzzy sets, and others. A variety of hybrid Multiple Criteria Decision Making (MCDM) methodologies will be integrated into these efforts. Researchers aim to enhance the robustness and adaptability of decision-making frameworks across diverse contexts by exploring these avenues. By leveraging advanced fuzzy set theories and hybrid MCDM techniques, future approaches will enable more comprehensive analysis of complex scenarios, ultimately supporting more informed and effective real-world decisions.

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Conflict of Interest

All authors assert that they do not have any conflicts of interest.

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