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An extended framework to evaluate sustainable suppliers in manufacturing companies using a new Pythagorean fuzzy entropy-SWARA-WASPAS decision-making approach

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Abstract

Purpose – The purpose of this study to introduce a new extended framework to evaluate and rank the sustainable suppliers based on the different sustainable criteria in the manufacturing companies using a new fuzzy decision-making approach.

Design/methodology/approach – This paper introduces a new approach using decision-making and Pythagorean fuzzy sets (PFSs) to assess the best sustainable supplier. To doing so, this study integrated the entropy, stepwise weight assessment ratio analysis (SWARA) and weighted aggregates sum product assessment (WASPAS) methods under PFSs. To calculate the criteria weights, the combined entropy-SWARA method is used to compute the objective weight and subjective weight, respectively. Furthermore, the WASPAS model is utilized to rank sustainable supplier alternatives.

Findings – The results of the analysis found that occupational health and safety systems had the highest rank among other criteria, followed by green product and eco-design, green R&D and innovation and green technology. In addition, the findings of the paper demonstrated that the extended approach was efficient and useful for selecting and evaluating the best sustainable supplier in the manufacturing companies.

Originality/value – Recent years have witnessed a number of studies aimed at incorporating the sustainability standards into the supplier selection problem; however, only a little research has been conducted on developing a fuzzy method for decision-making in a manner to assess and choose suppliers with high sustainability in the insurance market, encompassing the three above-mentioned sustainability criteria.

Keywords Sustainable supplier, Sustainability, Supply chain management, Pythagorean fuzzy sets, Sustainable development, SWARA, WASPAS

Paper type Research paper

1. Introduction

Currently, the global market has become highly competitive and is witnessing a gradual rise in the number of companies and organizations that outsource raw materials and services to

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suppliers (Azadnia *et al.*, 2015). Consequently, suppliers are playing a significant role in achieving corporate competitive edge and improving the performance of a company (Marshall *et al.*, 2019; Ekinci, 2019). In this regard, the supply chain management (SCM) field, in turn, faces challenges in selecting the optimal supplier(s) from among multiple suppliers available, realizing which requires making strategic decisions (Azadnia *et al.*, 2015; Azadnia *et al.*, 2011). Furthermore, with the recent rise of the popular subject "sustainability", scholars and practitioners have placed their focus on the field of sustainable SCM (S-SCM) (Kamble *et al.*, 2020; Qian *et al.*, 2020). Firms are expected to improve their supply chain activities pertaining to sustainability in such a manner that improves their overall sustainability level. This is necessary not only for being more responsive to the demanding social/environmental legislation but also for addressing the growing market services from various stakeholder collections (Govindan *et al.*, 2013). In recent years, many scholars have attempted to devise effective solutions to the sustainable supplier selection problem. Various studies (Abbas Mardani *et al.*, 2020; Tirkolaee *et al.*, 2019) have examined the scenarios where purchasers must define the optimum measure of products to demanding each time from each supplier, in such a way that the production plan requirements can be met, while also satisfying the given limitations.

Currently, the convergence of green/environmental and S-SCM has received significant attention of the researchers of this field (Büyüközkan and Çifçi, 2011). Moreover, S-SCM refers to managing not only the material, capital and information flows but also the collaboration among corporations with the supply chain and simultaneously considering the objectives of all the three sustainable development dimensions, which are generally derived from the requirements of customers and stakeholders (Yildizbasi *et al.*, 2018). In this regard, the attention on environmental management will be shifted from locally optimizing the environmental aspects to considering the complete supply chain in the course of producing, consuming and customer service (Linton *et al.*, 2007). The concept of sustainability originated from some ancient cultural practices; however, the recent literature has also attracted the significant attention of several scholars and practitioners regarding sustainability and environment (Lambrechts *et al.*, 2018; Tur-Porcar *et al.*, 2018).

To choose a sustainable supplier, the available suppliers' performance must be assessed based on various relevant criteria (Kannan, 2018; Bai and Sarkis, 2010; Luthra *et al.*, 2017). Such criteria have *per se* complicated the relationship between themselves, which needs to be given careful consideration by the evaluation methodology adopted in any case. The challenge of choosing a SS can be described as a conventional supplier selection problem through which social/environmental factors are considered in choosing and monitoring the presentation of suppliers (Genovese *et al.*, 2010). In the evaluation of sustainability, several researchers studying "sustainable supplier" have focused only on the economic and environmental parameters (Azadnia *et al.*, 2015; Fu *et al.*, 2012; Büyüközkan and Çifçi, 2012). Recently, the literature has witnessed only a little research on the effect of social aspects when assessing the sustainable suppliers (Bai *et al.*, 2019) or, in some cases, together with the environmental and economic aspects (Memari *et al.*, 2019; Mohammed *et al.*, 2019; Ghadimi *et al.*, 2019).

As people continue to become progressively awake of the environmental and social concerns, S-SCM has received great concentration from researchers in current years (Abbas Mardani *et al.*, 2020; Abdel-Basset and Mohamed, 2020; Hussain and Malik, 2020). For a company to succeed, the manner through which it chooses an appropriate sustainable supplier is very important; thus, the problem of sustainable supplier selection has become a significant decision-making challenge for supply chain managers (Song *et al.*, 2017). Recently, most firms and organizations have been centered on sustainability in SCM. This is mainly because the stakeholders, market and environmental regulations enacted by public institutes, along with the growth of customers' awareness, have relentlessly called for necessitating sustainability in all aspects of development. This reveals that a pressing need exists for a systematic sustainability-focused system of evaluation that can be implemented to sustainable supplier selection.

Newly, (Yager, 2013, 2014) announced the concept of Pythagorean fuzzy sets (PFSs), which are an extension of intuitionistic fuzzy sets (IFSs). In recent times, numerous studies on PFSs have been introduced and utilized it to solve various multiple-criteria decision-making (MCDM) problems (Fei and Deng, 2020, Wang and Li, 2020; Liu *et al.*, 2020). Rani *et al.* (2019b) studied the technique for order preference by similarity to ideal solution (TOPSIS) model with a similarity measure to handle the sustainable supplier selection problem under the PFSs context. Khan *et al.* (2019) extended a Dombi aggregation operator and utilized it for developing a new decision-making approach. However, only very few studies are available on the assessment and evaluation of the sustainable supplier selection problem under PFSs.

The criteria weights are significant mechanisms in the MCDM procedure. Criteria weights are of two varieties: objective and subjective weights (Jian Liu *et al.*, 2015; Diakoulaki *et al.*, 1995; Goldstein, 1990). To compute the objective criteria weights, many researchers have established various procedures-based on information measures and score functions (Rani *et al.*, 2020; Xiao, 2020). For calculating the subjective criteria weights, SWARA is an effective and comparatively fresh method (Kersuliene *et al.*, 2010). Mardani *et al.* (2017) provided a comprehensive assessment of stepwise weight assessment ratio analysis (SWARA) and weighted aggregates sum product assessment (WASPAS) approaches. Keshavarz Ghorabaee *et al.* (2018) discussed a hybrid procedure with SWARA, criteria importance through intercriteria correlation (CRITIC) and evaluation based on distance from average solution (EDAS) models to tackle the MCDM problems.

Further, many new MCDM techniques have been introduced under different uncertainty contexts. The WASPAS method, pioneered by Zavadskas *et al.* (2012), is an innovative approach. This approach is an association of the weighted sum method (WSM) and the weighted product method (WPM). Mishra *et al.* (2019) suggested the intuitionistic fuzzy sets-WASPAS (IF-WASPAS) model to assess the Telephone Service Providers (TSPs) in Madhya Pradesh in India. Gireesha *et al.* (2020) developed the improved WASPAS model for selecting cloud service providers under IFSs. Pamučar *et al.* (2019) introduced an approach using linguistic neutrosophic numbers (LNN) and the WASPAS to evaluate hazardous materials in transportation. Keshavarz Ghorabaee *et al.* (2019) established a model with WASPAS procedure under interval type-2 fuzzy sets (IT2FSs) to evaluate sustainable manufacturing strategies. However, a review of the literature reveals only limited research on sustainable supplier selection, especially in insurance firms. For companies to achieve sustainable development, appropriate suppliers must be selected based on sustainability standards (social, environmental and economic factors). Recent years have witnessed a number of studies aimed at incorporating the sustainability standards into the supplier selection problem; however, only a little research has been conducted on developing a fuzzy method for decision-making in a manner to assess and select suppliers with high sustainability in the insurance market, encompassing the three above-mentioned sustainability criteria.

Due to imprecise knowledge, the vague human mind, time restrictions and lack of information, to evaluate and analyze the sustainable suppliers is a significant and uncertain decision-making problem of manufacturing firms. Since the PFSs (Yager, 2013; Yager, 2014) have more effective capability than IFSs to manage the uncertainty and imprecision occurred in several real-life MCDM issues, as a result, several studies related to PFSs have been presented and applied for diverse purposes (Fei and Deng, 2020; Lei Wang and Li, 2020; Yi Liu *et al.*, 2020). Due to this motivation, the present study is focused under PFSs environment to assess sustainable suppliers in the manufacturing firms in the India context. In addition, this study introduced a new fuzzy decision-making approach to identify, rank and evaluate the main criteria of sustainable supplier selection in the universal appeal for all industries such as Indian manufacturing companies based on expert opinions and literature review, wherein the preference information is given in the form of PFSs. Many articles were employed the PFSs in many application areas, though none of them have utilized the PFSs based methodologies in evaluating the sustainable suppliers in the manufacturing companies. To the best of the authors' knowledge, this is the first work that proposes a collective decision-making framework based on the Pythagorean fuzzy entropy-SWARA-WASPAS (PFE- SWARA-WASPAS) to rank, select and evaluate the main criteria of sustainable suppliers in the manufacturing companies. This method can deal with higher degrees of uncertainty and contribute to several MCDM models in expert and intelligent systems that can handle the inherent fuzziness using a more powerful way. Accordingly, this research is focused mainly on accomplishing the following objectives:

(1) To extend the integrated entropy-SWARA-WASPAS method to the MCDM method that can be used to the assessment of sustainable supplier selection in manufacturing companies.

(2) To develop a combined entropy measure and SWARA method to effectively calculate the criteria weights on PFSs in manufacturing companies.

(3) A comparison of the outcomes of the introduced method with those of other existing models is illustrated.

(4) To confirm the results, a sensitivity analysis is made to examine the sustainable supplier selection process in insurance companies, considering the three sustainability criteria.

The paper is structured as Section 2 gives an existing work of sustainable supplier selection and decision-making models. Section 3 discusses some simple conceptions and the proposed method. Section 4 elaborates the real case study of sustainable supplier selection and illustrates a comparative study and sensitivity analysis. Finally, the discussion and conclusion are presented in Section 5.

2. Literature review

2.1 Sustainable supplier selection

Sustainable SCM refers to integrating and realizing an enterprise's social, environmental and economic goals completely in accordance with serious business procedures in a way to enhance the longstanding economic assessment of the enterprise (Craig, 2011). Evaluating the appropriateness of the available suppliers related to the main sustainability standards helps enterprises advance toward sustainable development and simultaneously considers the associated risks. For logistics managers, evaluating and selecting a sustainable supplier for manufacturing services with minimum risks through S-SCM is a key issue, especially when considering various criteria for making strategic decisions.

Researchers in this field have discussed the ways to improve supplier capacities for enlightening their environmental developments, either by holding the required authorizations or by presenting sustainable facets (Luthra *et al.*, 2017; Zhu *et al.*, 2019; dos Santos *et al.*, 2019). The sustainable supplier selection problem is essentially an extension of the traditional problem of supplier selection that additionally considers the different criteria of selecting and monitoring the performance of suppliers (Gören, 2018). In recent years, researchers have emphasized sustainability in supplier selection procedures (Kellner and Utz, 2019; Alikhani *et al.*, 2019; Pishchulov *et al.*, 2019).

Girubha (2016) and Bai and Sarkis (2010) evaluated the suppliers based on only one sustainability criterion, i.e. environmental perspective. However, as discussed earlier, sustainability holds two other pillars as well (economic and social aspects), which have not been investigated extensively in recent years. Therefore, this study presents an inclusive model that considers not only all the three sustainability pillars but also the business perspective. In addition, the feasibility of introduced model is certified through a case study.

2.2 Related work

Formulating the right criteria is a key challenge in the supplier selection processes. In these processes, the criteria are considered related to three dimensions: social, environmental and economic. The social facet is related to social problems, namely work-related health and safety, employees' rights and welfare and information revelation (Luthra *et al.*, 2017). The environmental aspect refers to pollution-related problems (Raza and Rathinam, 2017). In this respect, the predominant criteria include environmental management structures, resources consumption, eco-design and reduce, reuse and recycle (3Rs). The economic aspect, on the other hand, is expected to capitalize on the income flow that can be produced, and simultaneously minimize the capital yielding this income (Gören, 2018). Parameters such as cost, quality, service, delivery, technology and flexibility are the predominant criteria in the economic facet (Weber *et al.*, 1991; Yu *et al.*, 2019).

A firm must manage the sustainable supplier selection criteria properly and have effective execution practices to sustain its legitimacy and provide an appropriate public image (Luthra *et al.*, 2017). According to (Kumar *et al.*, 2016), an important concern for companies in recent years is to manage the SCM with a concentration on a sustainable supplier selection process. The literature contains various evaluation criteria for concrete scenarios to address the problem of sustainable supplier selection (Foroozesh *et al.*, 2019; Memari *et al.*, 2019; Zhou Xu *et al.*, 2019). Although most studies in this field consider the three sustainability dimensions as the evaluation criteria, each study has added some different sub-criteria. Accordingly, this research is centered on applying fuzzy decision-making methods to sustainable criteria selection and supplier selection.

Wang and Lee (2009) studied a fuzzy hierarchical approach by adopting the TOPSIS model to address the SS problem in a way to adapt fuzziness circumstances and offer more goals and criteria weights. In another project, Chan *et al.* (2008) developed an efficient methodology considering both quantitative and qualitative attributes with fuzzy analytic hierarchy process (AHP) that is applicable to global supplier selection. Guneri *et al.* (2009) endeavored to assess the SS problem by combining fuzzy and linear programming procedures. Further, Luthra *et al.* (2017) integrated AHP and Višekriterijumsko Kompromisno Rangiranje (VIKOR) to design an assessment framework for sustainable supplier selection. Furthermore, fuzzy AHP and TOPSIS were combined by Kannan *et al.* (2013) for ranking the suppliers by considering the environmental aspects. Subsequently, they designed a linear model capable of order allocation to consider the green supplier selection problem. Utilizing AHP in decision-making processes, Mani *et al.* (2014) focused on social sustainable supplier selection by considering the social factors. A green supplier selection model was introduced by Lee *et al.* (2009) for the high-technology industry for supplier rating. Buyukozkan and Cifci (2011) planned a fuzzy MCDM procedure comprising six evaluation criteria. Further, they utilized a fuzzy ANP procedure to find a rank to the sustainable supplier selection problem. Considering the social, environmental and economic sustainability criteria along with their accompanying sub-criteria, Amindoust *et al.* (2012) discussed a fuzzy ranking model applicable to sustainable supplier selection. Kannan *et al.* (2013) considered the fuzzy AHP to derive the optimum number of order quantities for each supplier. In another project, Azadnia *et al.* (2015) introduced a model by integrating the fuzzy

AHP and multi-objective linear programming, that is, applicable to sustainable supplier selection, as well as the multi-period lot-sizing problems regarding various criteria. Liao *et al.* (2019) suggested an innovative approach using the ANP under the hesitant fuzzy linguistic set to choose low-carbon suppliers. A novel model was introduced by Hsu *et al.* (2013) to choose suppliers centered on carbon management issues. They used the decision-making trial and evaluation laboratory (DEMATEL) method to select the suppliers centered on carbon management in green SCM. Awasthi *et al.* (2010) modified a fuzzy multiple criteria analysis model to analyze the suppliers' environmental performance in the supply chain. In addition, they integrated linguistic ratings with the fuzzy TOPSIS for determining the final performance score of each candidate. Bai and Sarkis (2010) applied a grey system and the rough set theory to incorporate sustainable supplier selection problem and have an effective decision-making process. Jauhar *et al.* (2014) presented a model to effectively address the sustainable supplier selection problem based on satisfaction factors versus sustainable factors.

3. Research method

3.1 Preliminaries

In this section, some fundamental concepts related to intuitionistic fuzzy sets (IFSs), PFSs and information measures (entropy and divergence measures) of PFSs are presented.

Definition 2.1. (Atanassov, 1986). An intuitionistic fuzzy set (IFS) M in a finite universe of discourse $U = \{u_1, u_2, \ldots, u_n\}$ is defined as

$$M = \{\langle u_i, \mu_M(u_i), \nu_M(u_i)\rangle | u_i \in U\}, \tag{1}$$

where $\mu_M : U \to [0, 1]$ is the degree of membership and $\nu_M : U \to [0, 1]$ the degree of non-membership of the element $u_i \in U$ in M such that $0 \le \mu_M(u_i) + \nu_M(u_i) \le 1$. The hesitant degree of $u_i \in U$ in M is expressed by $\pi_M(u_i) = 1 - \mu_M(u_i) - \nu_M(u_i)$. For ease, the intuitionistic fuzzy number (IFN) is denoted by $\alpha = M(\mu_\alpha, \nu_\alpha)$, which satisfies $\mu_\alpha, \nu_\alpha \in [0, 1]$ and $0 \le \mu_\alpha + \nu_\alpha \le 1$.

Definition 2.2. (Yager, 2013, 2014). A Pythagorean fuzzy set (PFS) X in a finite universe of discourse U is defined as

$$X = \{\langle u_i, X(\mu_X(u_i), \nu_X(u_i))\rangle | u_i \in U\}, \tag{2}$$

where $\mu_X : U \to [0, 1]$ and $\nu_X : U \to [0, 1]$ designate the membership and nonmembership of the element $u_i \in U$ to X, under the constraint that $0 \le (\mu_X(u_i))^2 + (\nu_X(u_i))^2 \le 1$. For each $u_i \in U$, the hesitancy degree is specified by $\pi_X(u_i) = \sqrt{1 - \mu_X^2(u_i) - \nu_X^2(u_i)}$. For easiness, Zhang and Xu (2014) indicated PFN by $\eta = (\mu_\eta, \nu_\eta)$, which fulfills $\mu_\eta, \nu_\eta \in [0, 1]$ and $0 \le \mu_\eta^2 + \nu_\eta^2 \le 1$.

Definition 2.3. (Peng and Yang (2016). Let $\eta = (\mu_\eta, \nu_\eta)$ be the PFN. The score value and accuracy degree of η are termed as

$$S(\eta) = (\mu_\eta)^2 - (\nu_\eta)^2, \hbar(\eta) = (\mu_\eta)^2 + (\nu_\eta)^2, \tag{3}$$

where $S(\eta) \in [-1, 1]$ and $\hbar(\eta) \in [0, 1]$.

Because $S(\eta) \in [-1, 1]$, then, a normalized score value is given as

Definition 2.4. Let $\eta = (\mu_\eta, \nu_\eta)$ be the PFN. Then, the normalized score and the uncertainty functions of η are defined by,

$$S^*(\eta) = \frac{1}{2}(\mathrm{S}(\eta)+1), \hbar^{\circ}(\eta) = 1 - \hbar(\eta), \tag{4}$$

such that $S^*(\eta),\ \hbar^{\circ}(\eta) \in [0,1]$.

Definition 2.5. (Yager, 2013, 2014). Let $\eta = (\mu_\eta, \nu_\eta), \eta_1 = (\mu_{\eta_1}, \nu_{\eta_1})$, and $\eta_2 = (\mu_{\eta_2}, \nu_{\eta_2})$ be PFNs. Then, the different operations on PFNs are given by

$$\eta^c = (\nu_\eta, \mu_\eta);$$

$$\eta_1 \oplus \eta_2 = \left(\sqrt{\mu_{\eta_1}^2 + \mu_{\eta_2}^2 - \mu_{\eta_1}^2\mu_{\eta_2}^2}, \nu_{\eta_1}\nu_{\eta_2}\right);$$

$$\eta_1 \otimes \eta_2 = \left(\mu_{\eta_1}\mu_{\eta_2}, \sqrt{\nu_{\eta_1}^2 + \nu_{\eta_2}^2 - \nu_{\eta_1}^2\nu_{\eta_2}^2}\right);$$

$$\lambda\eta = \left(\sqrt{1-(1-\mu_\eta^2)^\lambda}, (\nu_\eta)^\lambda\right), \lambda > 0;$$

$$\eta^\lambda = \left((\mu_\eta)^\lambda, \sqrt{1-(1-\nu_\eta^2)^\lambda}\right), \lambda > 0.$$

Definition 2.6. Rani *et al.* (2019a). Let $X \in \mathrm{PFS}(U)$ be PFNs, then an entropy measure is given as follows:

$$E(X) = 1 - \frac{1}{n}\sum_{i=1}^{n}\left[\left(\mu_X^2(u_i) - \nu_X^2(u_i)\right)I_{\left[\mu_X^2(u_i)\ge\nu_X^2(u_i)\right]} + \left(\nu_X^2(u_i) - \mu_X^2(u_i)\right)I_{\left[\mu_X^2(u_i)<\nu_X^2(u_i)\right]}\right]. \tag{5}$$

3.2 Proposed PF-entropy-SWARA-WASPAS method

Here, we discuss an integrated entropy-SWARA-WASPAS framework for PFSs to estimate the objective and subjective criteria weights and assess the rank of options. The procedural structure of the introduced approach is given by

Step 1: Frame the decision-making procedure and create the decision matrix.

Let $R = \{R_1, R_2, \ldots, R_m\}$ and $C = \{C_1, C_2, \ldots, C_n\}$ be a set of alternatives and criteria for decision-making procedure, respectively. A set of DEs $\{E_1, E_2, \ldots, E_l\}$ gives their decisions on each option R_i over the criterion C_j in the form of Linguistic Terms (LTs). Let $N = (g_{ij}^{(k)}), \ \forall i, j$ be the DM specified by experts.

Step 2: Estimate the DEs' weights.

For evaluating the expert weight, let $E_k = (\mu_k, \nu_k)$ be the rating of DE provided by experts, then, the DE weight is estimated by (Rani *et al.*, 2019a):

$$\omega_k = \frac{\left(\mu_k^2 + \pi_k^2 \times \left(\frac{\mu_k^2}{\mu_k^2+\nu_k^2}\right)\right)}{\sum_{k=1}^{\ell}\left(\mu_k^2 + \pi_k^2 \times \left(\frac{\mu_k^2}{\mu_k^2+\nu_k^2}\right)\right)}, k = 1(1)\ell. \tag{6}$$

Clearly, $\omega_k \ge 0$ and $\sum_{k=1}^{\ell}\omega_k = 1$.

Step 3: Aggregate the PF-DM (APF-DM).

For this purpose, the PF-weighted averaging operator (PFWAO) proposed by (Yager, 2013, 2014) is utilized; then, $\mathbb{Z} = (\xi_{ij})_{m\times n}$, such that

$$\xi_{ij} = (\mu_{ij}, \nu_{ij}) = \text{PFWA}_{\lambda}\left(g_{ij}^{(1)}, g_{ij}^{(2)}, \ldots, g_{ij}^{(\ell)}\right) = \left(\sqrt{1 - \prod_{k=1}^{\ell}(1-\mu_k^2)^{\lambda_k}}, \prod_{k=1}^{\ell}(\nu_k)^{\lambda_k}\right). \quad (7)$$

Step 4: Computation of criteria weights

To achieve the weight, we apply the following procedure:

Case 1. Compute the objective weight w_j^o using the entropy measure:

$$w_j^o = \frac{1 - \sum_{i=1}^{m}(E(\xi_{ij}))}{n - \sum_{j=1}^{n}\sum_{i=1}^{m}(E(\xi_{ij}))}, \quad j = 1(1)n. \quad (8)$$

Case 2. Estimate the subjective weight w_j^s using SWARA model

The phases for computing the criteria weights are given by

Step 4.1: Evaluate the crisp degree. Score values $S^*(\xi_{kj})$ of PFNs using Eq. (4) are computed.

Step 4.2: Determine the ranking and comparative significance of criteria. The preferences of criteria-based on the DEs' opinion from the higher significance to the minimum significance criterion are estimated. The comparative significance is performed by comparing criterion j and criterion $j-1$.

Step 4.3: Calculate the comparative coefficient k_j as follows:

$$k_j = \begin{cases} 1, & j = 1 \\ s_j + 1, & j > 1, \end{cases} \quad (9)$$

where s_j is the comparative significance value (Keršuliene *et al.*, 2010).
Step 4.4: Estimate the weights. The recalculated weight p_j is given by,

$$p_j = \begin{cases} 1, & j = 1 \\ \dfrac{k_{j-1}}{k_j} & j > 1 \end{cases} \quad (10)$$

Step 4.5: Estimate the subjective weight. The criteria weights are computed by,

$$w_j^s = \frac{p_j}{\sum_{j=1}^{n} p_j}. \quad (11)$$

Case 3. Determine the combined weight in the following relation:

$$w_j = \vartheta w_j^s + (1-\vartheta) w_j^o, \quad (12)$$

where ϑ is the coefficient of the decision precision parameter.

Step 5: Generate normalized PF-DM.

Here, the APF-DM $\mathbb{Z} = (\xi_{ij})_{m\times n}$ is transformed into normalized PF-DM $\mathbb{N} = (\tilde{\xi}_{ij})_{m\times n}$, where

$$\tilde{\xi}_{ij} = \begin{cases} \xi_{ij} = (\mu_{ij}, \nu_{ij}), & j \in C_b \\ (\xi_{ij})^c = (\nu_{ij}, \mu_{ij}), & j \in C_n, \end{cases} \tag{13}$$

where C_b and C_n signify the benefit and cost-type criteria sets, respectively.

Step 6: Compute the WSM $\mathbb{C}_i^{(1)}$ measure as follows:

$$\mathbb{C}_i^{(1)} = \sum_{j=1}^{n} w_j \tilde{\xi}_{ij}. \tag{14}$$

Step 7: Appraise the WPM $\mathbb{C}_i^{(2)}\mathbb{C}_i^{(2)}$ measure as follows:

$$\mathbb{C}_i^{(2)} = \prod_{j=1}^{n} w_j \tilde{\xi}_{ij}. \tag{15}$$

Step 8: Determine the WASPAS measure for each option as

$$\mathbb{C}_i = \lambda \mathbb{C}_i^{(1)} + (1-\lambda)\mathbb{C}_i^{(2)}, \tag{16}$$

where λ is the combining coefficient of decision accuracy.

Step 9: Preference order of the choices according to descending values of Ci.

4. Case study

In this section, to support and validate the proposed approach, a real case study has been considered from the manufacturing sector. In this regard, four manufacturing companies in India have been selected to evaluate sustainable suppliers. To illustrate the application of the integrated framework, this study identifies four types of companies included chemical, automobile, construction equipment and electronics/telecommunications manufacturing (the names of companies due to privacy are not given). To identify the main criteria to evaluate and select sustainable suppliers, in this paper, a survey study using the expert's interview and literature review has been carried out. To doing so, in the first step, we have identified 20 criteria to evaluate and select the best sustainable suppliers from the previous literature (Table 1). In the second step, the selected criteria are classified into three main aspects of sustainability, including social, economic and environmental. The details of these criteria and aspects are provided in Table 1 and Figure 1. In the next step of the study research methodology, a group of decision-makers from these companies are invited. In total, four potential suppliers from the manufacturing companies are selected as study alternatives.

Here, the linguistic values are described in a qualitative manner, i.e. words or sentences. LTs are more suitable for addressing uncertain real-life MCDM problems; thus, many researchers have defined diverse LTs. The LTs for preference ordering of DEs, sustainable supplier selection options and criteria are listed in Tables 2 and 3.

The DEs' weights are estimated by using Table 2 and Eq. (6) and listed in Table 4. Table 5 lists the linguistic terms provided by experts for criteria weights. Applying Eq. (7) and Table 3, the APF-DM, are created and listed in Table 6.

Next, the objective criteria weights are computed using Eqs. (5) and (8) and Table 6, and given as follows:

Criteria	Sub-criteria	References
Environmental aspect	Green product and eco-design (C_1)	Al-Sheyadi *et al.* (2019), Kazancoglu (2018), Pan *et al.* (2019), Hamed *et al.* (2018)
	Green warehousing (C_2)	Awasthi and Kannan (2016), Fallahpour *et al.* (2017), Rostamzadeh *et al.* (2015)
	Green R&D and innovation (C_3)	Huang *et al.* (2017), Amindoust *et al.* (2012), Guo *et al.* (2017)
	Green transportation (C_4)	Awasthi and Kannan (2016), Fallahpour *et al.* (2017), Tate *et al.* (2012)
	Green technology (C_5)	Govindan and Rajendran, 2015, Liao *et al.* (2016), Bali (2013), Tseng (2011)
	Environmental management system (C_6)	Amindoust *et al.* (2012), Kannan *et al.* (2013), Büyüközkan (2012)
	Pollution control (C_7)	Kannan *et al.* (2013), Amindoust *et al.* (2013), Guo *et al.* (2017)
	Resource consumption (C_8)	Kannan *et al.* (2013), Guo *et al.* (2017), Qin *et al.* (2017)
Social aspects	Human (stakeholders/workers) rights (C_9)	Fallahpour *et al.* (2017), Mani *et al.* (2014), Xu *et al.* (2013)
	Occupational health and safety systems (C_{10})	Luthra *et al.* (2017), Azadnia *et al.* (2015), Song *et al.* (2017)
	Social responsibility (C_{11})	Azadnia *et al.* (2015), Mani *et al.* (2014), Kannan *et al.* (2013)
	Labor practices and decent work (C_{12})	Awasthi *et al.* (2018), Delai and Takahashi (2013), Delai and Takahashi (2013)
	Information disclosure (C_{13})	A. Amindoust *et al.* (2012), Govindan and Rajendran (2015), Luthra *et al.* (2017)
Economic aspects	Profit on product (C_{14})	Luthra *et al.* (2017), Roy *et al.* (2019), Azimifard *et al.* (2018)
	Technological and financial capability (C_{15})	Luthra *et al.* (2017), Azimifard *et al.* (2018), Kuo and Lin (2012)
	Reduced cost maintenance (C_{16})	Sinha and Anand (2018), Chan *et al.* (2008), Yücenur *et al.* (2011)
	Price of product (C_{17})	Galankashi *et al.* (2016), Luthra *et al.* (2017), Çebi and Otay (2016)
	Carbon tax (C_{18})	Arabsheybani *et al.* (2018), Rao *et al.* (2017), Viswanadham and Samvedi (2013)
	Financial capability (C_{19})	Amindoust *et al.* (2012), Luthra *et al.* (2017), Kuo *et al.* (2010)
	Delivery service and flexibility (C_{20})	Amindoust *et al.* (2012), Görener *et al.* (2017), Ghadimi and Heavey (2014)

Table 1.
Selected criteria for sustainable supplier evaluation

$$w_j^o = (0.0547, 0.0496, 0.0565, 0.0601, 0.0353, 0.0471, 0.0604, 0.0501, 0.0472, 0.0411, 0.0371, 0.0505, 0.0485, 0.0444, 0.0531, 0.0656, 0.0468, 0.0414, 0.0567, 0.0538).$$

By applying SWARA approach discussed in Tables 7 and 8, the subjective criteria weights are given by

$$w_j^s = (0.0600, 0.0532, 0.0563, 0.0485, 0.0567, 0.0542, 0.0404, 0.0483, 0.0407, 0.0629, 0.0451, 0.0496, 0.0474, 0.0498, 0.0416, 0.0530, 0.0444, 0.0492, 0.0481, 0.0506).$$

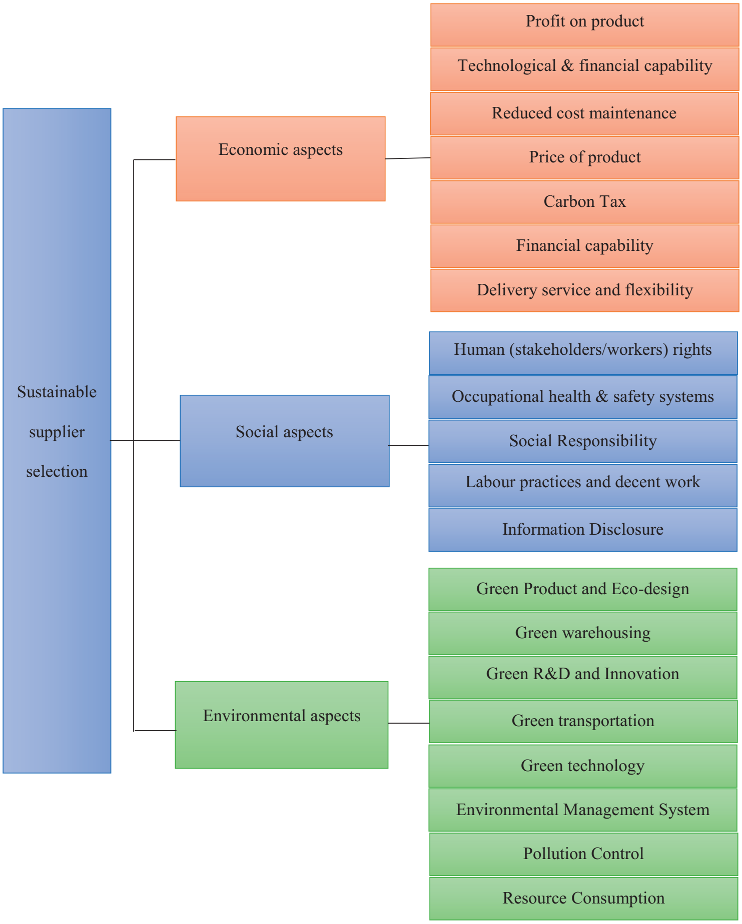

Figure 1.
Hierarchical procedure for SSS criteria

LTs	Pythagorean fuzzy numbers (PFNs)
Absolutely skilled (ES)	(0.9500, 0.1000)
Very very skilled (VVS)	(0.8000, 0.2500)
Very skilled (VS)	(0.7000, 0.3500)
Skilled (S)	(0.5000, 0.5500)
Less skilled (LS)	(0.4500, 0.6000)
Very less skilled (VLS)	(0.1500, 0.9000)

Table 2.
LTs for rating the DEs' weights

Now, the combined weight of criteria for $\vartheta = 0.5$, is calculated as follows:

$$w_j = (0.0573, 0.0514, 0.0564, 0.0543, 0.0460, 0.0507, 0.0504, 0.0492, 0.0440, 0.0520, 0.0411, 0.0500, 0.0480, 0.0471, 0.0474, 0.0593, 0.0456, 0.0453, 0.0524, 0.0522).$$

Using Eq. (13), the normalized PF-DM is calculated and depicted in Table 9. Then, from Table 9, Eq. (14) and Eq. (15), the measures of WSM $\mathbb{C}_i^{(1)}$ and WPM $\mathbb{C}_i^{(2)}$ and the corresponding

LTs	PFNs
Perfectly high (PH)	(0.9500, 0.2000)
Very high (VH)	(0.8500, 0.3500)
High (H)	(0.7000, 0.4000)
Medium-high (MH)	(0.6500, 0.4500)
Average (A)	(0.5000, 0.5500)
Medium low (ML)	(0.4000, 0.6500)
Low (L)	(0.3500, 0.7500)
Very low (VL)	(0.2500, 0.8500)
Very very low (VVL)	(0.2000, 0.9500)

Table 3.
Assessment ratings of options and criteria in terms of LTs

DEs	Linguistic values	PFNs	Weights
E_1	Skilled (S)	X (0.5000, 0.5500)	0.2092
E_2	Very very skilled (VVS)	X (0.8000, 0.2500)	0.4210
E_3	Extremely skilled (ES)	X (0.7000, 0.3500)	0.3698

Table 4.
DEs' weights for rating the SSS option

Criteria	E^1				E^2				E^3			
	R^1	R^2	R^3	R^4	R^1	R^2	R^3	R^4	R^1	R^2	R^3	R^4
C_1	MH	A	H	VH	ML	H	A	H	A	VH	H	MH
C_2	A	H	A	VH	H	MH	H	VH	A	H	VH	ML
C_3	L	A	MH	A	VL	L	MH	VH	A	MH	H	H
C_4	H	A	A	H	ML	A	MH	VH	MH	H	A	VH
C_5	L	ML	VH	H	VL	L	H	VH	ML	ML	H	MH
C_6	VH	H	ML	A	PH	H	ML	H	VH	A	L	VL
C_7	MH	A	ML	MH	H	VH	H	MH	MH	L	A	MH
C_8	H	A	MH	H	VH	MH	VH	H	A	A	MH	H
C_9	H	ML	L	VH	A	L	ML	H	H	L	ML	H
C_{10}	H	VH	H	MH	PH	H	A	MH	PH	A	MH	H
C_{11}	A	A	H	VH	MH	VL	PH	VH	A	A	MH	H
C_{12}	PH	MH	H	VH	PH	A	H	MH	H	A	ML	A
C_{13}	MH	L	H	VH	H	L	VH	MH	A	ML	A	MH
C_{14}	H	MH	A	VH	PH	H	MH	VH	H	ML	H	MH
C_{15}	H	MH	H	VH	MH	H	ML	MH	H	A	H	VH
C_{16}	VH	A	H	A	MH	A	H	ML	A	ML	A	H
C_{17}	L	A	H	MH	VL	ML	H	MH	L	MH	PH	A
C_{18}	MH	H	H	VH	PH	A	H	MH	H	A	VH	H
C_{19}	A	MH	H	L	H	VL	VH	ML	ML	H	MH	VL
C_{20}	H	VH	A	H	VH	H	A	MH	A	H	ML	A

Table 5.
Subjective evaluation values scored by the DEs for the SSS option

	R_1	R_2	R_3	R_4
C_1	(0.505, 0.566, 0.652)	(0.747, 0.407, 0.525)	(0.633, 0.457, 0.625)	(0.728, 0.406, 0.552)
C_2	(0.602, 0.481, 0.637)	(0.680, 0.420, 0.601)	(0.747, 0.407, 0.525)	(0.763, 0.440, 0.474)
C_3	(0.433, 0.630, 0.645)	(0.522, 0.582, 0.624)	(0.670, 0.431, 0.605)	(0.756, 0.404, 0.514)
C_4	(0.584, 0.513, 0.629)	(0.591, 0.489, 0.641)	(0.573, 0.505, 0.645)	(0.828, 0.360, 0.431)
C_5	(0.335, 0.750, 0.571)	(0.380, 0.690, 0.616)	(0.801, 0.370, 0.471)	(0.766, 0.395, 0.507)
C_6	(0.906, 0.277, 0.320)	(0.642, 0.450, 0.621)	(0.383, 0.685, 0.620)	(0.555, 0.565, 0.611)
C_7	(0.672, 0.428, 0.604)	(0.691, 0.510, 0.513)	(0.589, 0.498, 0.636)	(0.650, 0.450, 0.612)
C_8	(0.738, 0.425, 0.524)	(0.573, 0.505, 0.645)	(0.759, 0.405, 0.510)	(0.700, 0.400, 0.592)
C_9	(0.633, 0.457, 0.625)	(0.361, 0.728, 0.583)	(0.390, 0.670, 0.632)	(0.742, 0.389, 0.546)
C_{10}	(0.929, 0.231, 0.290)	(0.694, 0.438, 0.571)	(0.610, 0.478, 0.632)	(0.670, 0.431, 0.605)
C_{11}	(0.680, 0.420, 0.601)	(0.584, 0.549, 0.598)	(0.929, 0.231, 0.290)	(0.808, 0.368, 0.461)
C_{12}	(0.906, 0.258, 0.336)	(0.538, 0.527, 0.657)	(0.622, 0.479, 0.620)	(0.674, 0.460, 0.578)
C_{13}	(0.630, 0.461, 0.625)	(0.370, 0.711, 0.598)	(0.738, 0.425, 0.524)	(0.710, 0.427, 0.560)
C_{14}	(0.864, 0.439, 0.247)	(0.609, 0.491, 0.624)	(0.646, 0.449, 0.617)	(0.798, 0.384, 0.465)
C_{15}	(0.680, 0.420, 0.601)	(0.630, 0.461, 0.625)	(0.609, 0.491, 0.623)	(0.789, 0.389, 0.476)
C_{16}	(0.674, 0.460, 0.578)	(0.467, 0.582, 0.666)	(0.642, 0.450, 0.621)	(0.564, 0.525, 0.638)
C_{17}	(0.313, 0.791, 0.527)	(0.535, 0.548, 0.643)	(0.851, 0.310, 0.425)	(0.603, 0.485, 0.633)
C_{18}	(0.860, 0.306, 0.409)	(0.555, 0.515, 0.654)	(0.770, 0.381, 0.512)	(0.726, 0.409, 0.553)
C_{19}	(0.579, 0.512, 0.635)	(0.569, 0.563, 0.599)	(0.766, 0.395, 0.507)	(0.342, 0.740, 0.580)
C_{20}	(0.738, 0.425, 0.524)	(0.742, 0.389, 0.546)	(0.467, 0.585, 0.663)	(0.617, 0.473, 0.629)

Table 6.
APF-DM for SSS problem

Criteria	E_1	E_2	E_3	PFNs	Crisp values $S^*(\xi_{kj})$
C_1	H	H	VH	(0.669, 0.520, 0.531)	0.589
C_2	A	MH	MH	(0.535, 0.597, 0.598)	0.465
C_3	H	H	MH	(0.592, 0.550, 0.589)	0.524
C_4	A	ML	MH	(0.442, 0.671, 0.595)	0.372
C_5	MH	H	H	(0.597, 0.545, 0.589)	0.530
C_6	VH	A	MH	(0.570, 0.598, 0.564)	0.484
C_7	VL	L	L	(0.277, 0.837, 0.473)	0.188
C_8	MH	A	ML	(0.433, 0.672, 0.601)	0.368
C_9	ML	L	VL	(0.278, 0.829, 0.486)	0.195
C_{10}	VH	VH	H	(0.722, 0.504, 0.473)	0.634
C_{11}	A	ML	ML	(0.355, 0.729, 0.586)	0.298
C_{12}	ML	A	MH	(0.460, 0.652, 0.603)	0.394
C_{13}	ML	A	A	(0.406, 0.681, 0.609)	0.350
C_{14}	MH	ML	MH	(0.474, 0.653, 0.591)	0.399
C_{15}	L	ML	VL	(0.291, 0.808, 0.513)	0.216
C_{16}	VH	MH	L	(0.564, 0.628, 0.536)	0.462
C_{17}	VL	ML	A	(0.347, 0.746, 0.568)	0.282
C_{18}	ML	MH	ML	(0.460, 0.663, 0.590)	0.386
C_{19}	H	A	L	(0.440, 0.682, 0.584)	0.364
C_{20}	ML	A	H	(0.483, 0.635, 0.603)	0.415

Table 7.
Subjective assessment of criteria in terms of LTs for the SSS problem

score values $S^*(\mathbb{C}_i^{(1)})$ and $S^*(\mathbb{C}_i^{(2)})$ are computed for each sustainable supplier selection option and provided in Table 10. Using Eq. (16), the WASPAS measure ($\mathbb{C}_i$) for each sustainable supplier selection option is evaluated and depicted in Table 10 (for $\lambda = 0.5$). Subsequently, the ranking order of four sustainable supplier selection alternatives is presented as $R_4 \succ R_1 \succ R_3 \succ R_2$, which reveals that R_4 is the optimal sustainable supplier selection option.

Criteria	Crisp values	Comparative importance of criteria value (s_j)	Coefficient (k_j)	Recalculated weight (p_j)	Final weight (w_j)
C_{10}	0.634	–	1.000	1.000	0.0629
C_1	0.589	0.048	1.048	0.954	0.0600
C_5	0.530	0.059	1.059	0.901	0.0567
C_3	0.524	0.006	1.006	0.896	0.0563
C_6	0.484	0.040	1.040	0.862	0.0542
C_2	0.465	0.019	1.019	0.846	0.0532
C_{16}	0.462	0.003	1.003	0.843	0.0530
C_{20}	0.415	0.047	1.047	0.805	0.0506
C_{14}	0.399	0.016	1.016	0.792	0.0498
C_{12}	0.394	0.005	1.005	0.788	0.0496
C_{18}	0.386	0.008	1.008	0.782	0.0492
C_4	0.372	0.014	1.014	0.771	0.0485
C_8	0.368	0.004	1.004	0.768	0.0483
C_{19}	0.364	0.004	1.004	0.765	0.0481
C_{13}	0.350	0.014	1.014	0.754	0.0474
C_{11}	0.298	0.052	1.052	0.717	0.0451
C_{17}	0.282	0.016	1.016	0.706	0.0444
C_{15}	0.216	0.066	1.066	0.662	0.0416
C_9	0.195	0.021	1.021	0.648	0.0407
C_7	0.188	0.007	1.007	0.643	0.0404

Table 8.
Criteria weights by the SWARA process for the SSS problem

	R_1	R_2	R_3	R_4
C_1	(0.566, 0.505, 0.652)	(0.407, 0.747, 0.525)	(0.457, 0.633, 0.625)	(0.406, 0.728, 0.552)
C_2	(0.481, 0.602, 0.637)	(0.420, 0.680, 0.601)	(0.407, 0.747, 0.525)	(0.440, 0.763, 0.474)
C_3	(0.630, 0.433, 0.645)	(0.582, 0.522, 0.624)	(0.431, 0.670, 0.605)	(0.404, 0.756, 0.514)
C_4	(0.584, 0.513, 0.629)	(0.591, 0.489, 0.641)	(0.573, 0.505, 0.645)	(0.828, 0.360, 0.431)
C_5	(0.335, 0.750, 0.571)	(0.380, 0.690, 0.616)	(0.801, 0.370, 0.471)	(0.766, 0.395, 0.507)
C_6	(0.277, 0.906, 0.320)	(0.450, 0.642, 0.621)	(0.685, 0.383, 0.620)	(0.565, 0.555, 0.611)
C_7	(0.672, 0.428, 0.604)	(0.691, 0.510, 0.513)	(0.589, 0.498, 0.636)	(0.650, 0.450, 0.612)
C_8	(0.738, 0.425, 0.524)	(0.573, 0.505, 0.645)	(0.759, 0.405, 0.510)	(0.700, 0.400, 0.592)
C_9	(0.633, 0.457, 0.625)	(0.361, 0.728, 0.583)	(0.390, 0.670, 0.632)	(0.742, 0.389, 0.546)
C_{10}	(0.929, 0.231, 0.290)	(0.694, 0.438, 0.571)	(0.610, 0.478, 0.632)	(0.670, 0.431, 0.605)
C_{11}	(0.680, 0.420, 0.601)	(0.584, 0.549, 0.598)	(0.929, 0.231, 0.290)	(0.808, 0.368, 0.461)
C_{12}	(0.906, 0.258, 0.336)	(0.538, 0.527, 0.657)	(0.622, 0.479, 0.620)	(0.674, 0.460, 0.578)
C_{13}	(0.630, 0.461, 0.625)	0.370, 0.711, 0.598)	(0.738, 0.425, 0.524)	(0.710, 0.427, 0.560)
C_{14}	(0.864, 0.439, 0.247)	(0.609, 0.491, 0.624)	(0.646, 0.449, 0.617)	(0.798, 0.384, 0.465)
C_{15}	(0.420, 0.680, 0.601)	(0.461, 0.630, 0.625)	(0.491, 0.609, 0.623)	(0.389, 0.789, 0.476)
C_{16}	(0.460, 0.674, 0.578)	(0.582, 0.467, 0.666)	(0.450, 0.642, 0.621)	(0.525, 0.564, 0.638)
C_{17}	(0.791, 0.313, 0.527)	(0.548, 0.535, 0.643)	(0.310, 0.851, 0.425)	(0.485, 0.603, 0.633)
C_{18}	(0.306, 0.860, 0.409)	(0.515, 0.555, 0.654)	(0.381, 0.770, 0.512)	(0.409, 0.726, 0.553)
C_{19}	(0.512, 0.579, 0.635)	(0.563, 0.569, 0.599)	(0.395, 0.766, 0.507)	(0.740, 0.342, 0.580)
C_{20}	(0.425, 0.738, 0.524)	(0.389, 0.742, 0.546)	(0.585, 0.467, 0.663)	(0.473, 0.617, 0.629)

Table 9.
Normalized PF-DM for the SSS problem

SSS	WSM $\mathbb{C}_i^{(1)}$	$S^*(\mathbb{C}_i^{(1)})$	WPM $\mathbb{C}_i^{(2)}$	$S^*(\mathbb{C}_i^{(2)})$	$S^*(\mathbb{C}_i)$	Ranking
R_1	(0.668, 0.503, 0.549)	0.597	(0.559, 0.604, 0.568)	0.474	0.535	2
R_2	(0.534, 0.577, 0.618)	0.476	(0.507, 0.603, 0.616)	0.446	0.461	4
R_3	(0.612, 0.533, 0.585)	0.545	(0.537, 0.600, 0.593)	0.464	0.505	3
R_4	(0.645, 0.508, 0.570)	0.579	(0.585, 0.573, 0.574)	0.507		1

Table 10.
Computational assessment of PF-Entropy-SWARA-WASPAS method

4.1 Sensitivity analysis

Here, we perform a sensitivity analysis for the variation of parameter (λ) values. Various values of $\lambda \in [0, 1]$ are considered for investigation. The variation of λ can facilitate us to appraise the sensitivity of the WASPAS approach from WPM to WSM. The ranking orders with the parameter values are depicted in Table 11 and Figure 2. Figure 2 shows that, in each set, supplier-4 is ranked "1", followed consecutively by supplier-1 (rank 2), supplier-3 (rank 3), and supplier-2 (rank 4), when $\lambda = 0.0$ to 0.6. Further, supplier-1 is ranked "1", followed consecutively by supplier-4 (rank 2), supplier-3 (rank 3) and supplier-2 (rank 4), when $\lambda = 0.7$ to 1.0. Accordingly, it is seen that the introduced method maintains good stability over a diverse range of values of the parameter. Furthermore, the subjective weights evaluated by the SWARA method to enhance the sensitivity of the proposed method. This discussion reveals that the use of diverse parameter values can advance the permanence of the developed methodology.

4.2 Comparison with an existing approach

To demonstrate the efficacy and exhibit the unique advantages of PF-Entropy-SWARA-WASPAS method, the PF-TOPSIS model (Zhang and Xu, 2014) is utilized to address the above problem as follows:

Steps 1–4: Similar to the previous procedure

Step 5: Assess the anti-ideal solution (A-IS) ϕ^{+} and ideal solution (IS) ϕ^{-}.

Table 11. WASPAS measure degree for SSS for different values of the parameter

λ	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
R_1	0.474	0.487	0.499	0.511	0.523	0.535	0.548	0.560	0.572	0.584	0.597
R_2	0.446	0.449	0.452	0.455	0.458	0.461	0.464	0.467	0.470	0.473	0.476
R_3	0.464	0.472	0.480	0.488	0.496	0.505	0.513	0.521	0.529	0.537	0.545
R_4	0.507	0.514	0.521	0.529	0.536	0.543	0.550	0.557	0.565	0.572	0.579

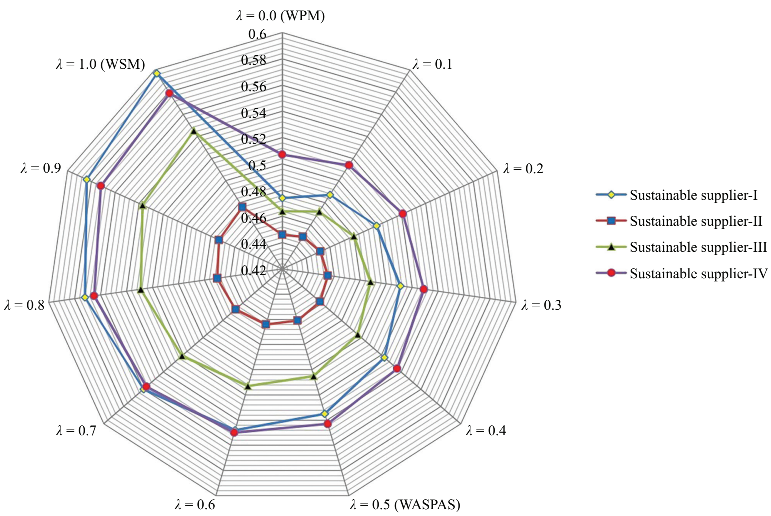

Figure 2. Sensitivity outcomes of $\mathbb{C}_i$ values with decision precision parameter (λ) values

Step 6: Assess the degrees of discrimination from PF-IS and PFA-IS.

$$D(R_i,\phi^+) = \frac{1}{2}\sum_{j=1}^{n}\left[w_j\left(\left|\mu_{\eta_{ij}}^2 - \mu_{\phi_j^+}^2\right| + \left|\nu_{\eta_{ij}}^2 - \nu_{\phi_j^+}^2\right| + \left|\pi_{\eta_{ij}}^2 - \pi_{\phi_j^+}^2\right|\right)\right]. \tag{17}$$

Generally, the smaller the $D(R_i,\ \phi^+)$, the better the alternative R_i is; let

$$D_{\min}(R_i,\phi^+) = \min_{1\le i\le m} D(R_i,\phi^+), \tag{18}$$

and

$$D(R_i,\phi^-) = \frac{1}{2}\sum_{j=1}^{n}\left[w_j\left(\left|\mu_{\eta_{ij}}^2 - \mu_{\phi_j^-}^2\right| + \left|\nu_{\eta_{ij}}^2 - \nu_{\phi_j^-}^2\right| + \left|\pi_{\eta_{ij}}^2 - \pi_{\phi_j^-}^2\right|\right)\right]. \tag{19}$$

Generally, the larger the $D(R_i,\ \phi^-)$, the better the alternative R_i is; let

$$D_{\max}(R_i,\phi^-) = \max_{1\le i\le m} D(R_i,\phi^-). \tag{20}$$

Step 7: Estimate the closeness coefficient (CC).

$$\mathbb{C}(R_i) = \frac{D(R_i,\phi^-)}{D(R_i,\phi^+) + D(R_i,\phi^-)}, \quad i = 1(1)m. \tag{21}$$

Next, the improved CC of each option is given by

$$\mathbb{R}(R_i) = \frac{D(R_i,\phi^-)}{D_{\max}(R_i,\phi^-)} - \frac{D(R_i,\phi^+)}{D_{\min}(R_i,\phi^+)}, \forall i. \tag{24}$$

Step 8: Select the maximum degree $\mathbb{R}(R_k)$, from the values $\mathbb{R}(R_i),\ i = 1(1)m$. Therefore, R_k is the best option.

From Table 6, the PF-IS and PFA-IS are assessed. The whole outcomes of the PF-TOPSIS model (Zhang and Xu, 2014) for the sustainable supplier selection are listed in Table 12.

$$\begin{aligned}\phi^+ = \{&(0.406, 0.728, 0.552), (0.407, 0.747, 0.525), (0.404, 0.756, 0.514),\\ &(0.828, 0.360, 0.431), (0.801, 0.370, 0.471), (0.277, 0.906, 0.320), (0.691, 0.510, 0.513),\\ &(0.759, 0.405, 0.510), (0.742, 0.389, 0.546), (0.929, 0.231, 0.290), (0.929, 0.231, 0.290),\\ &(0.929, 0.231, 0.290), (0.906, 0.258, 0.336), (0.738, 0.425, 0.524), (0.864, 0.439, 0.247),\\ &(0.389, 0.789, 0.476), (0.450, 0.642, 0.621), (0.310, 0.851, 0.425), (0.306, 0.860, 0.409),\\ &(0.395, 0.766, 0.507), (0.389, 0.742, 0.546)\}\end{aligned}$$

Options	$D(R_i,\phi^+)$	$D(R_i,\phi^-)$	$\mathbb{C}(R_i)$	Ranking	$\mathbb{R}(R_i)$	Ranking
R_1	0.1781	0.2234	0.5563	2	−0.1021	2
R_2	0.2961	0.1012	0.2548	4	−1.3354	4
R_3	0.1912	0.1964	0.5066	3	−0.2969	3
R_4	0.1671	0.2318	0.5812	1	0.0000	1

Table 12.
Ranking orders of PF-TOPSIS for the SSS problem

$$\phi^{-} = \{(0.566, 0.505, 0.652), (0.481, 0.602, 0.637), (0.630, 0.433, 0.645), (0.573, 0.505, 0.645), (0.335, 0.750, 0.571), (0.685, 0.383, 0.620), (0.589, 0.498, 0.636), (0.573, 0.505, 0.645), (0.361, 0.728, 0.583), (0.610, 0.478, 0.632), (0.584, 0.549, 0.598), (0.538, 0.527, 0.657), (0.370, 0.711, 0.598), (0.609, 0.491, 0.624), (0.491, 0.609, 0.623), (0.582, 0.467, 0.666), (0.791, 0.313, 0.527), (0.515, 0.555, 0.654), (0.740, 0.342, 0.580), (0.585, 0.467, 0.663)\}$$

Table 10 shows that R_4 is the optimal sustainable supplier, and the preference order of sustainable supplier selection alternative is $R_4 \succ R_1 \succ R_3 \succ R_2$. Hence, we observe that the optimal choice remains the same, i.e., R_4 with the introduced approach. Furthermore, the introduced approach is appropriate for the cases where the PF-TOPSIS model fails. The above discussion shows that the introduced method for handling the MCDM problems has the given advantages:

In Zhang and Xu (2014), the largest PF-IS is used as a benchmark, realizing which is unrealistic in practice. Contrarily, in our approach, the best performing alternatives based on the PFWAO score from the available settings are used as benchmarks that are more realistic in terms of not only knowing the IS and A-IS performances of the alternatives on the given attributes but also making a relative comparison of their performances.

From the existing procedures, they (Zhang and Xu (2014) and Peng and Yang (2016) have been incapable of recognizing or preferences the options appropriately, their analogous procedures may not produce appropriate outcomes. Otherwise, the introduced approach can reduce their deficiencies and can thus rank the options appropriately, making it more appropriate to address decision-making problems.

In addition, a method is proposed to compute more accurate criteria weights. Calculating the criteria weights is the main challenge in the MCDM procedure (Ghorabaee *et al.*, 2016). In the introduced framework, the objective (obtained by entropy) and the subjective (computed by SWARA process) weights are aggregated, and the combined weights are applied in integrated PF-Entropy-SWARA-WASPAS method.

5. Discussions and conclusion

The main objective of this study to introduce a new extended framework to evaluate and rank the sustainable suppliers based on the different sustainable criteria in the manufacturing companies using a new decision-making under Pythagorean fuzzy environment. In this regard, a survey approach using experts' interview and literature review has been conducted to identify the important criteria to evaluate and rank the sustainable suppliers in the manufacturing companies in the India context. This study mainly evaluated sustainability and selected sustainable suppliers in manufacturing companies associated with the three pillars of sustainability, namely, environmental, social and economic aspects.

According to the results of the survey approach, in total, 20 criteria including occupational health and safety systems, green product and eco-design, green technology, green R&D and innovation, environmental management system, green warehousing, reduced cost maintenance, delivery service and flexibility, profit on product, labor practices and decent work, carbon tax, green transportation, resource consumption, financial capability, information disclosure, social responsibility, price of product, technological and financial capability, human (stakeholders/workers) rights and pollution control have been identified to evaluate and rank the sustainable suppliers. In the following step, this study, integrated the entropy, SWARA and WASPAS approaches under PFSs. To compute the weights of the criteria, the combined entropy-SWARA method and the WASPAS approach is employed to rank sustainable supplier options. The results of this article indicated that occupational health and safety systems (0.0629) had the highest rank among other criteria follow by green product and eco-design (0.0600), green technology (0.0567) green R&D and innovation (0.0563).

Over the recent years, decisions regarding the selection of sustainable supplier have become important as companies and firms more and more compete on economic, social and environmental supply chain capabilities (Geyi *et al.*, 2020; Liu *et al.*, 2020). To achieve this goal, the managers in manufacturing companies required to understand numerous barriers or challenges for implementation of the assessment systems for sustainability-focused supplier in the supply chain process. All selected criteria to evaluate the sustainable suppliers can help the company's managers to handling several barriers or challenges among manufacturing companies in evolving sustainability features in sustainable supplier related decisions (Gupta *et al.*, 2020; Nazam *et al.*, 2020). Therefore, the paper current study can play an important role to understand many criteria and their rankings to choose the best sustainable supplier from the industrial view of point. The integrated framework could aid the manufacturing companies' practitioners, managers and policymakers to reach better results in their companies' performance and to make different ways to eliminate the possible barriers or challenges for effective decisions for sustainable supplier in the manufacturing companies.

In addition, the integrated framework has several managerial implications to help supply chain managers. First, the integrated framework presented can helps supply chain managers in reaching the objectives of sustainability of the company and also helps in achieving the maximum level of satisfaction from sustainable supplier selection process. Further, the integrated framework includes the knowledge of experts and managers of the company to enhance the effectiveness of the sustainable supplier selection process and support them to have a detailed understanding into the supplier's sustainability performance.

From the theoretical view, this study attempted to close a research gap since using a novel and comprehensive framework to select, rank and evaluate the sustainable supplier selection. In this regard, a comprehensive review using the current literature has been conducted to present a framework using sustainable development and supply chain management theories. To do so, in total, 20 criteria are classified based on three main aspects of sustainable development including social, environmental and economic (Table 1 and Figure 1).

The results of the analysis found that the extended approach was efficient and useful for selecting and evaluating the best sustainable supplier in the manufacturing companies. Moreover, the outcomes of the analysis indicated that the extended method is active and helpful to judge and rank the sustainable suppliers in manufacturing companies. Furthermore, a comparison was made, which demonstrated that the introduced approach is interesting and easy to use. Moreover, researchers can extend the research by utilizing various MCDM procedures (e.g. Additive Ratio Assessment (ARAS), Preference Ranking Organisation Method for Enrichment Evaluations (PROMETHEE), COPRAS (Complex Proportional Assessment of alternatives, or AHP) for appropriate sustainable supplier selection. We will continue our research with enthusiasm to make our approach valid to various additional problems, such as strategic supplier assessment and renewable energy assessment, among others.

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