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Improving sustainable supplier evaluation by an integrated MCDM method under pythagorean fuzzy environment

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Abstract

Sustainability plays a significant role in promoting competence and collaboration in supply chain management due to increased environmental awareness, tightened regulations, and government policies. The evaluation of sustainable suppliers and selecting the best one is indispensable for companies to promote sustainability. Due to multi-criteria nature of the supplier selection process, it has been considered as a multi-criteria decision making (MCDM) problem in many studies. In this study, a state-of-the-art MCDM method for sustainable supplier selection is developed by integrating AHP and TOPSIS techniques within the Pythagorean Fuzzy Sets (PFSs) linguistic setting. A Group Decision Making (GDM) environment is utilized due to superiority of group consensus over individual decisions. Finally, an apparel industry example is used to illustrate the effectiveness and feasibility of the proposed sustainable supplier selection method. A comparison with existing techniques and sensitivity analysis are done to verify and validate the given outcome.

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1. Introduction

The focus on sustainability in the context of supplier evaluation is increasing rapidly. Sustainability is not restricted by the liable practices within an organization's operations but covers the whole value chain. Due to rising energy prices and to respond to the changing needs of consumers and customers, organizations are under immense pressure of regulation changes and sustainability plays a significant role in promoting competence and collaboration in supply chain management. Thus, organizations are encouraged by stakeholders to formulate the objectives of sustainability and to handle the necessary operations to accomplish these objectives. Simply stated, sustainability is a long-term value creating business approach in the light of how a given organization runs under the social, environmental, and economical situations [1]. Sustainability is based upon the assumption that developing solutions strategies to achieve the given objectives foster companies' longevity [2]. Due to increased environmental awareness, tightened regulations, and government policies, the demand for sustainable and transparent suppliers are increasing worldwide. Sustainable supplier is an industry concern affecting an organization's supply chain management and logistics network in terms of social, environmental, and economical aspects and so supplier selection in the context of developing sustainable supply chain management can be regarded as a decisive operational task. The integration of social, environmental, and economic aspects should be taken into account when evaluating the sustainable suppliers that can enhance the supply chain performance. Nowadays, many of the organizations should have a suitable and accurate assessment of their suppliers to satisfy their needs and achieve sustainability. Besides, social, environmental, and economic factors should be applied to the process of sustainable supplier evaluation. Therefore, several factors considering quantitative and qualitative criteria need to be applied to the evaluation process. However, an exact quantitative value may not be employed due to some data cannot be represented by crisp values. Thus, a proper evaluation method is necessary not only to eliminate these constraints, but also to satisfy the objectives of the study.

Supplier evaluation is one of the significant activities of the sustainable supply chain management. The

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challenge of determining an effective framework based on sustainability assumptions for supplier selection processes in supply chains is thoroughly examined in this paper. Due to nature of sustainable supplier evaluation process, this analysis entails a suitable multi-criteria analysis and solution methodology. Multi-Criteria Decision-Making (MCDM) process, on the other hand, puts forward a concept in which the most suitable candidate among the predefined ones is selected by assessing them in terms of several criteria. MCDM methods gets to be increasingly popular in supplier evaluations and sustainability assessments. Several significant improvements have been observed on MCDM techniques since the development of modern MCDM theory in the early sixties. Conventional MCDM methods are constantly being applied to evaluate decision problems to select an alternative among many. There exist various types of MCDM techniques and more are introduced day in and day out. Multi-Objective Optimization on the basis of Ratio Analysis (MOORA) [3], AHP (Analytical Hierarchy Process) [4], TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions) [5] are a few of the many. One of the significant problems in these MCDM techniques is how to represent the evaluations of the Decision Makers (DMs) exactly. Subjective representations can benefit from the subjective judgments of DMs, but they are challenging to eliminate bias instigated by the DMs' lack of experience and knowledge. Objective representations, on the other hand, have solid theoretical and mathematical basis, and the assessment does not rely on human judgments, but does not reveal the subjective opinions of DMs, and disregard the DMs' experience and knowledge buildup. In addition, many DMs have a tendency to make use of linguistic expressions in stating their judgments as a result of ambiguous decision environment. The DMs' linguistic evaluations are usually collected by quantitative and qualitative assessments in order to assess the relative significance and performance of the decision criteria to make scientific and accurate decisions. Therefore, Zadeh [6] developed the fuzzy set concept, in which the opinions of DMs are collected as a linguistic evaluations and he introduced a mathematical and scientific foundation to make operations and compute with the given linguistic values. But the conventional fuzzy set theory has some restrictions when it comes to dealing with complex linguistic evaluations due to vagueness and subjectivity associated with the given judgments.

In order to overcome these restrictions on conventional fuzzy set, an extension is proposed by Atanassov [7] and Intuitionistic Fuzzy (IF) sets are developed. Thus, many MCDM problems utilized the notion of IF set theory to address the decision data. On the other hand, there are some areas in which the IF sets also have some deficiencies. To better address the imprecision and vagueness of the conventional crisp, fuzzy or IF sets, the Pythagorean Fuzzy Set (PFS) concept is developed. Yager extended IF sets into PFSs theory, defining elements having membership degree and non-membership degree, in which the square sum of them is a maximum of 1 [8,9]. Since PFSs can effectively represent the fuzzy characteristics of things, they have been applied to several MCDM problems in earlier studies. Varieties of new solution techniques have been formed to deal with the difficulties aroused during the sustainable supplier evaluation process. One of the latest favored methods to evaluate and analyze these problems is based on MCDM concept. Although MCDM approaches are devised to find faster and efficient solutions to problems, if the methodology is not set straight and structured adequately, MCDM cannot guarantee to find the best solution [10]. On the other hand, if MCDM methods are adequately applied, they can play an indispensable role of finding the solution to the problem. The weights of criteria can be determined most suitably by AHP approach and a fairly accurate ranking can be accomplished by TOPSIS method. The AHP is based on creating a decision hierarchy to better comprehend the sub-problems and analyze them independently by comparing them with one another in a rational and consistent way. TOPSIS technique depends on the concept of shortest distance from positive ideal solution and the farthest distance from negative ideal solution to unravel the complex domains having inconsistent criteria [10]. Besides, the PFSs are used to provide a better viewpoint for a further satisfactory modelling in complex real case situations. Additionally, contribution of multiple DMs in decision making process is crucial for most decision making problems. Wherefore the involvement of more than one DMs benefits the decision quality and thus many MCDM methods are also applied under a group decision making (GDM) environment [12]. Since GDM also benefits in reducing subjectivity and minimizing bias in the decision making process. The contributions of the research are delivered in succeeding sentences:

-to the best of author's knowledge, there is no prior research applying integration of PF-AHP (Pythagorean Fuzzy AHP) and PF-TOPSIS (Pythagorean Fuzzy TOPSIS) approach under GDM setting as a MCDM method in the sustainable supplier selection problem area;

-justification for PFSs environment's impact on decision problems is added distinctive contribution to the present literature. This is a pioneering research that endorses the effect of PFSs on decision-making in sustainable supplier selection; and

-the contribution to the real-world cases is that developing a ready to use, flexible method modified for sustainable supplier selection. The companies can simply customize the proposed method by varying the criteria, alternatives or decision problem that reflect their own specific environments.

-this new methodology allows to capture the vagueness and hesitation associated with the DMs' judgments with the aid of PFSs' enhanced solution environment.

So, an integrated, state of art, solution method is developed in this research. The developed approach lets dealing the hesitation of the initial information with explicitly by making use of GDM.

The flow of this paper is structured as: Initially, the review of the current literature is introduced. Subsequently, the development of the proposed approach is presented to evaluate and prioritize the sustainable suppliers. After that, a practical case along with the numerical analysis is examined. And a discussion and analysis section are presented before the last section. Finally, summary and conclusion of the research is presented.

2. Literature Review

The evaluation of sustainable suppliers would be best dealt with as a distinctive MCDM problem due to its typical nature of taking multi-criteria into account in a simultaneous matter to rank a finite number of sustainable supplier alternatives. The evaluation process of alternatives is primarily based on the reliable judgment of the industry experts, rather than the given outcome of arithmetic techniques. In the literature, many of the earlier studies have examined and developed suitable sustainable supplier selection criteria. Besides, a lot of research have applied the proposed techniques in different environments. However, there are no study explicitly dealing with the evaluation of sustainable suppliers under GDM setting by the use of integrated AHP and TOPSIS techniques within the PFSs linguistic environment. There are two recent study [13,14] combining the AHP and TOPSIS techniques under PFSs setting. Some parts might indeed seem similar to the presented study as a first look. However, with a detailed comparison, there are distinct differences between the presented methodology and others. First of all, this study develops a novel priority MCDM framework by integrating PFSs objective world environment to capture uncertainty and hesitancy involved in DMs' judgments. The AHP method is recommended to derive proper criteria weights, and the TOPSIS method is implied as a distance-based closeness to ideal solution approach under GDM setting to get rid of bias in the decision-making process. On the other hand, the mentioned studies utilize only the AHP and TOPSIS methods under the PFSs environment. For instance, the mentioned studies [13,14] applies interval-valued PFSs setting in AHP evaluations, that is rather different solution environment than the presented study in this paper although they also utilizes PFSs environment. If a further comparison is made among the presented paper and cited study, details of the AHP and TOPSIS applications under PFS is also entirely dissimilar. This manuscript uses a 9-point linguistic scale in evaluations, and they apply a 10-point interval-valued scale. The presented study applies normalization and weighting for the given relation matrix, while these steps are excluded in the mentioned studies. They use generalized Pythagorean fuzzy standardized distance operator to determine positive ideal and negative ideal solution. At the same time, we apply another set of distinct equations for their calculations. This list can elongate if the details are further inquired. Therefore, the presented manuscript has its distinctions and superiorities. But we have carefully checked all related studies and take some benefits of them using proper citations of mentioned studies. The subsequent sections present a brief review of current publications that focus on sustainable suppliers, AHP, and TOPSIS techniques under PFSs setting.

2.1. Sustainable supplier selection

Countless studies on various areas of sustainable supplier selection have emerged [1,15,16]. Though these researchers have developed different models for the evaluation of sustainable suppliers, a small number of them assessed the suppliers from the GDM perspective. Xu et al. [17] developed an AHP approach for sustainable supplier selection by applying interval type 2 fuzzy environment. Rabbani et al. [18] introduced an interval valued fuzzy GDM approach to evaluate sustainability performance of suppliers in the sustainable supply chain management. Baset et al. [19] provided a MCDM GDM approach under neutrosophic environment to solve the problem of sustainable supplier selection and illustrate the effectiveness of the proposed approach in importing field. Song and Li [20] developed large scale GDM method to handle sustainable supplier selection problem by considering the incomplete multigranular linguistic sets. Pishchulov et al. [21] proposed voting AHP methodology based on GDM environment to illustrate the application of a real world sustainable supplier selection problem to their offered method. Foroozesh et al. [22] developed GDM approach to assess the sustainable supplier risks in terms of ecologic, economic, and social aspects. There are several more studies on the subject of sustainable supplier selection. However, as it could be comprehended from above analysis, there are no study using an integrated MCDM approach under PFSs environment for a GDM setting to evaluate sustainable supplier selection.

2.2. PFSs MCDM approaches

The application of PFSs theory in MCDM GDM problem has been stated in literature to a limited extent. Utilization of PFSs in a decision-making environment for sustainable supplier evaluation appears to be relatively new and unexplored research area. The presented research emerges some remarkable managerial insights. There are very few studies exist explicitly dealing with the supplier selection problem in the context of MCDM. As far as the author is aware of, there is no earlier study exist on the subject of selecting a suitable supplier in the context of sustainability. And the PFSs concept is a relatively new research area. Currently, there are many studies exist in PFSs as either aggregation operator proposals or regular MCDM applications but the number of PF-AHP and PF-TOPSIS MCDM studies are limited as illustrated in Table 1.

This review of literature on the subject inform that many crucial features have been designated rare attention by researchers so far. Limited number of scientific studies exist in the areas of PF-AHP and PF-TOPSIS MCDM approaches but non exist integrating both of them together in GDM environment. To the best knowledge of the author, there are no prior contributions about sustainable supplier evaluations in the context of PFSs linguistic environment. Thus, this is the state of the art methodology to solve sustainable supplier evaluation problem through the proposed method which makes it a more realistic and reliable approach.

Table 1. PF-AHP and PF-TOPSIS MCDM Literature

Reference #	Integrated Method	GDM	Application Area
[13]	Interval Valued PF-AHP and PF-TOPSIS	-	Service Quality
[14]	Interval Valued PF-AHP and PF-TOPSIS	-	Green Supplier
[23]	Interval Valued PF-AHP	-	Regional Development
[24]	Interval Valued PF-AHP	-	Risk Assessment
[25]	Interval Valued PF-AHP	-	Risk Assessment
[26]	Interval Valued PF-AHP	-	Risk Assessment
[27]	Interval Valued PF-AHP		Risk Assessment
[28]	PF-TOPSIS	-	Airline Service Quality
[29]	Interval Valued PF-TOPSIS	-	Illustrative
[30]	Choquet Integral PF-TOPSIS	-	Illustrative
[31]	Hesitant PF-TOPSIS	-	Energy Project
[32]	PF-TOPSIS	-	Cloud Service Provider
[33]	PF-TOPSIS	-	Risk Assessment
[34]	Hesitant PF-TOPSIS	-	Illustrative
[35]	PF-TOPSIS	GDM	Illustrative
[36]	Interval Valued PF-TOPSIS	-	Partner Selection

3. Methodology

3.1. Preliminaries

Initial development of PFS concept has been made by Yager and Abbasov [8,9,37]. Initial proposal has been made to extend IF set in order to create a characteristic theory to handle the fuzziness and uncertainty by considering the both membership and nonmembership degrees in pairs $(\mu_P(x): X \rightarrow [0,1], v_P(x): X \rightarrow [0,1])$ [8,37].

Let X be a fixed set in a non-empty universe, a PFS P in X is denoted as:

$$P = \{\langle x, \mu_P(x), v_P(x)\rangle\}, \quad (1)$$

Subjected to:

$$0 \leq \left(\mu_P(x)\right)^2 + \left(v_P(x)\right)^2 \leq 1, \quad (2)$$

$$\pi_P(x) = \sqrt{1 - \left(\mu_P(x)\right)^2 + \left(v_P(x)\right)^2}, \forall x \in \mathrm{X}, \tag{3}$$

The PFSs' arithmetic operations are presented by using two PFS number,

$p_1 = \left(\mu_{P_1}(x), v_{P_1}(x)\right)$ and $p_2 = \left(\mu_{P_2}(x), v_{P_2}(x)\right)$ and $\lambda > 0$, as follows [28,38]:

$$p_1 \otimes p_2 = \left(\mu_{P_1}(x).\mu_{P_2}(x), \sqrt{\left(v_{P_1}(x)\right)^2 + \left(v_{P_2}(x)\right)^2 - \left(v_{P_1}(x)\right)^2.\left(v_{P_2}(x)\right)^2}\right), \tag{4}$$

$$p_1 \oplus p_2 = \left(\sqrt{\left(\mu_{P_1}(x)\right)^2 + \left(\mu_{P_2}(x)\right)^2 - \left(\mu_{P_1}(x)\right)^2.\left(\mu_{P_2}(x)\right)^2}, v_{P_1}(x).v_{P_2}(x)\right), \tag{5}$$

$$if\ \mu_{P_1}(x) \leq \min\left\{\mu_{P_2}(x), \frac{\mu_{P_2}(x).\pi_{P_1}(x)}{\pi_{P_2}(x)}\right\}, v_{P_1}(x) \geq v_{P_2}(x),$$

$$Then, \frac{p_1}{p_2} = \left(\frac{\mu_{P_1}(x)}{\mu_{P_2}(x)}, \sqrt{\frac{\left(v_{P_1}(x)\right)^2 - \left(v_{P_2}(x)\right)^2}{1 - \left(v_{P_2}(x)\right)^2}}\right), \tag{6}$$

$$if\ \mu_{P_1}(x) \geq \mu_{P_2}(x), v_{P_1}(x) \leq min\left\{v_{P_2}(x), \frac{v_{P_2}(x).\pi_{P_1}(x)}{\pi_{P_2}(x)}\right\},$$

$$Then, p_1 \ominus p_2 = \left(\sqrt{\frac{\left(\mu_{P_1}(x)\right)^2 - \left(\mu_{P_2}(x)\right)^2}{1 - \left(\mu_{P_2}(x)\right)^2}}, \frac{v_{P_1}(x)}{v_{P_2}(x)}\right), \tag{7}$$

$$p_1{}^{\lambda} = \left(\mu_{P_1}(x)\right)^{\lambda}, \sqrt{1 - \left(1 - \left(v_{P_1}(x)\right)^2\right)^{\lambda}}, \tag{8}$$

$$\lambda * p_1 = \left(\sqrt{1 - \left(1 - \left(\mu_{P_1}(x)\right)^2\right)^{\lambda}}, \left(v_{P_1}(x)\right)^{\lambda}\right), \tag{9}$$

$$p_1{}^{C} = \left(v_{P_1}(x), \mu_{P_1}(x)\right), \tag{10}$$

Pythagorean Fuzzy Weighted Arithmetic (PFWA) Aggregation [8,9] operator is defined as follows:

$$PFWA = P_1^{\lambda} \otimes P_2^{\lambda}, \ldots, \otimes P_K^{\lambda} = \langle \sqrt{1 - \prod_{k=1}^{K}\left(1 - \left(\mu_{P_k}(x)\right)^2\right)^{\lambda}}, \prod_{k=1}^{K} v_{P_k}(x)^{\lambda} \rangle, \tag{11}$$

3.2. The Developed integrated MCDM method

The step wise representation of the developed approach is delivered through this section. The schematic representation is also given in Figure 2.

Step 1: Describe the criteria and alternatives

The Alternative set (A_i) for m alternative ($i = 1, 2, \ldots, m$) is assessed by the use of defined criteria set (C_j) for n criteria ($j = 1, 2, \ldots, n$).

Step 2: Estimate the DMs' priority weights

Table 2. Verbal terms to assess DMs and Alternatives [12]

Linguistic Variables	Abbreviations	[$\mu_P(x)$,	$v_P(x)$]
Extremely Important	EI	[0.85,	0.15]
Very Important	VI	[0.75,	0.25]
Important	I	[0.65,	0.35]
Medium Importance	MI	[0.50,	0.45]
Unimportant	U	[0.35,	0.65]
Very Unimportant	VU	[0.25,	0.75]
Extremely Unimportant	EU	[0.15,	0.85]

The level of individual weights ($\lambda_k, \sum_{k=1}^{K} \lambda_k = 1$) in DMs set ($D_k, k = 1, 2, \ldots, K$) can alter due to the different responsibilities, knowledges, and experiences of distinctive DMs. To be able to define the priorities of DMs and their individual weights, the subsequent steps has been applied.

-The verbal terms are expressed to define the priority levels of DMs.

-The linguistic statements for the priority of DMs in Table 2 are applied to calculate the DMs weights.

-The individual DMs priorities are fused together by applying the PFWA aggregation operator.

-The influence level of the k^{th} DM on the judgment is estimated by the Equation (Eq.) (12).

$$\lambda_k = \frac{\frac{\sqrt{\mu_{P_j}(x) - \left(v_{P_j}(x)\right)^2}}{2}}{\sum_{k=1}^{K} \frac{\sqrt{\mu_{P_j}(x) - \left(v_{P_j}(x)\right)^2}}{2}}, \text{ where } \sum_{k=1}^{K} \lambda_k = 1 \quad (12)$$

Step 3: Gather the evaluations of DMs for each criterion

-The verbal terms are expressed to define the judgments for criteria.

-The pairwise comparison ($\tilde{P}_j^{\,k}, j = 1, 2, \ldots, n,\ k = 1,2, \ldots, K$) is established for criteria and sub-criteria by the use of linguistic statements in Table 3.

The preference scale for PFSs AHP is established by applying the consistency conversion [39]. The detailed demonstration of how the PFSs linguistic scale for AHP is constructed is presented in Büyüközkan and Göçer [12].

Step 4: Establish the group consensus for individual assessments

-GDM matrix is established for each DM to evaluate criteria by the use of PFWA aggregation operator in Eq. (11).

Table 3. Linguistic statements for the priority of criteria [12]

Linguistic Statements		PFSs Values	
		[$\mu_P(x)$,	$v_P(x)$]
Equally Important	EI	[0.07,	0.30]
Intermediate	IV	[0.18,	0.49]
Moderately More Important	MI	[0.29,	0.60]
Intermediate	IV2	[0.39,	0.65]
Strongly More Important	SI	[0.50,	0.67]
Intermediate	IV3	[0.61,	0.66]
Very Strong Importance	VSI	[0.71,	0.61]
Intermediate	IV4	[0.82,	0.52]
Extremely More Important	EMI	[1.00,	0.00]

Table 4. RI Values [40]

N	RI	N	RI	n	RI
01	0.000	04	0.900	07	1.320
02	0.000	05	1.120	08	1.410
03	0.580	06	1.240	09	1.450

Step 5: Control the consistency of pairwise comparison matrix

Consistency Ratio (CR) is controlled for all pairwise matrix by the Eq. (13). The Random Index (RI) is adapted from [40]. Table 4 delivers RI table having up to 9 elements;

$$\mathrm{CR} = \frac{RI - \frac{\sum \boldsymbol{\pi_P}(x)_{ij}}{n}}{n-1}, \tag{13}$$

Here, n denotes the number of elements in each matrix. $\boldsymbol{\pi_P}(\boldsymbol{x})_{ij}$ denotes the hesitancy value. When the calculated CR is equal to or less than 0.10, the given matrices is considered as consistent. If the value of CR is above 0.10, then matrix is inconsistent, and the DMs should give their judgments once more.

Step 6: Compute each criterion weight

PFWA operator for aggregation defined in Eq. (11) is applied to fuse the assessment matrices. Each criterion weight ($\widetilde{w}_j$) by applying PFSs AHP method is calculated based on all DMs judgments.

Step 7: Define decision matrix for each DM

The opinions of DMs in the form of linguistic variables are converted by applying the scale in Table 2 and decision matrix $\left(A_{(k)_{ij}}\right)_{mxn}$ for each DM is established.

$$\mathrm{A}_{(\mathrm{k})_{\mathrm{ij}}} = \begin{bmatrix} \mathrm{a}_{11} & \cdots & \mathrm{a}_{1\mathrm{n}} \\ \vdots & \ddots & \vdots \\ \mathrm{a}_{\mathrm{m}1} & \cdots & \mathrm{a}_{\mathrm{mn}} \end{bmatrix}, \tag{14}$$

Step 8: Determine GDM matrix

The evaluations of each DM are fused by the use of Eq. (11) (PFWA aggregation operator) and GDM matrix is established.

$$\mathrm{A}_{\mathrm{ij}} = \begin{bmatrix} \mathrm{a}_{11} & \cdots & \mathrm{a}_{1\mathrm{n}} \\ \vdots & \ddots & \vdots \\ \mathrm{a}_{\mathrm{m}1} & \cdots & \mathrm{a}_{\mathrm{mn}} \end{bmatrix}, \tag{15}$$

Step 9: Setup weighted and normalized matrix

By the Eq. (10), the decision matrix is normalized. And then, Eq. (16) is used to construct weighted matrix. The criteria weighs are presented in Step 6.

$$\widetilde{\mathrm{R}}_{\mathrm{ij}} = \widetilde{\mathrm{w}}_{\mathrm{j}} \otimes \widetilde{\mathrm{x}}_{\mathrm{ij}}, \tag{16}$$

where $\tilde{r}_{ij} = (\mu_{\widetilde{A}}(x), \nu_{\widetilde{A}}(x)), j = 1, 2, \dots, n, i = 1, 2, \dots, m$.

Step 10: Calculate positive and negative ideal solution

Use Eq. (17) and Eq. (18) to find positive (A^{+}) and negative (A^{-}) ideal solutions, respectively.

$$\mathrm{A}^{+} = (\tilde{\mathrm{r}}_1^{+}, \tilde{\mathrm{r}}_2^{+}, \dots, \tilde{\mathrm{r}}_\mathrm{n}^{+}), \tilde{\mathrm{r}}_\mathrm{j}^{+} = \left(\mu_\mathrm{j}^{+}, \upsilon_\mathrm{j}^{+}, \pi_\mathrm{j}^{+}\right), \tag{17}$$

$$\mathrm{A}^{-} = (\tilde{\mathrm{r}}_1^{-}, \tilde{\mathrm{r}}_2^{-}, \dots, \tilde{\mathrm{r}}_\mathrm{n}^{-}), \tilde{\mathrm{r}}_\mathrm{j}^{-} = \left(\mu_\mathrm{j}^{-}, \upsilon_\mathrm{j}^{-}, \pi_\mathrm{j}^{-}\right), \tag{18}$$

Where $j = 1, 2, \dots, n$, suppose J_1 is the benefit type criterion, J_2 is the cost type criterion.

$$\mu_j^{+} = \left\{\left(\max_i\{\mu_{ij}\} \mid j \in J_1\right)\right\}, \left\{\left(\min_i\{\mu_{ij}\} \mid j \in J_2\right)\right\}, \tag{19}$$

$$v_j^{+} = \left\{\left(\min_i\{v_{ij}\} \mid j \in J_1\right)\right\}, \left\{\left(\max_i\{v_{ij}\} \mid j \in J_2\right)\right\},$$

$$\mu_j^{-} = \left\{\left(\min_i\{\mu_{ij}\} \mid j \in J_1\right)\right\}, \left\{\left(\max_i\{\mu_{ij}\} \mid j \in J_2\right)\right\},$$

$$v_j^{-} = \left\{\left(\max_i\{v_{ij}\} \mid j \in J_1\right)\right\}, \left\{\left(\min_i\{v_{ij}\} \mid j \in J_2\right)\right\},$$

Step 11: Calculate separation measures

Use Eq. (20) and Eq. (21) to calculate separation measures of negative and positive ideal solutions.

$$S_i^{+} = \sqrt{\frac{1}{2n}\sum_{j=1}^{n}\left[\left|{\mu_{ij}}^2 - {\mu_j^{*}}^2\right| + \left|{v_{ij}}^2 - {v_j^{*}}^2\right| + \left|{\pi_{ij}}^2 - {\pi_j^{*}}^2\right|\right]}, \quad (20)$$

$$S_i^{-} = \sqrt{\frac{1}{2n}\sum_{j=1}^{n}\left[\left|{\mu_{ij}}^2 - {\mu_j^{-}}^2\right| + \left|{v_{ij}}^2 - {v_j^{-}}^2\right| + \left|{\pi_{ij}}^2 - {\pi_j^{-}}^2\right|\right]}, \quad (21)$$

Step 12: Calculate closeness coefficient

Calculate the closeness coefficient for each alternative using the Eq. (22).

$$C_i^{+} = \frac{S_i^{-}}{S_i^{+} + S_i^{-}}, i = 1, 2, \ldots, m \qquad 0 \le C_i^{+} \le 1, \quad (22)$$

Step 13: Rank the alternatives.

The respective candidate is ranked according to the descending order of closeness coefficient (C_i^{+}).

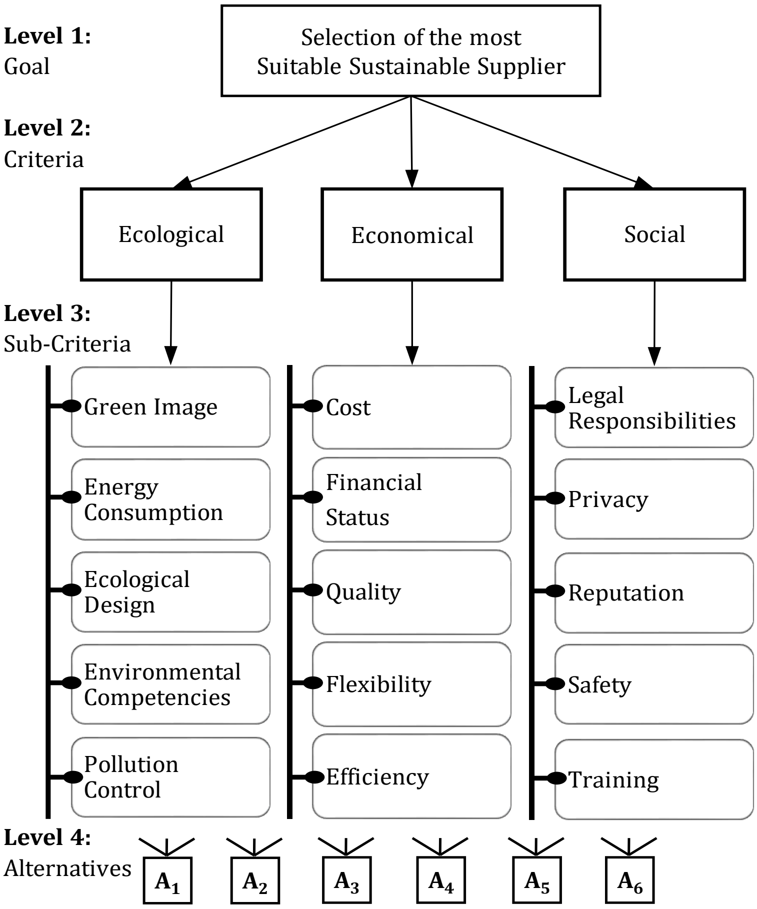

Figure 1. Hierarchical organization of evaluation structure.

Step 1: Define
-Decision criteria (C_j)
-Available alternatives (A_i)

Step 2: Determine
-DMs Weights (λ_k)

Step 3: Collect
-Pairwise assessment ($\tilde{P}_j{}^k$)

Step 4: Aggregate
-Individual criteria evaluations (PFWA)

Step 5: Check
-Consistency Ratio (CR)

Step 6: Construct
-Criteria Weights ($\widetilde{w}_j$)

Step 7: Determine
-Individual decision matrix $\left(A_{(k)_{ij}}\right)_{mxn}$

Step 8: Establish
-Aggregated decision matrix $\left(A_{ij}\right)_{mxn}$

Step 9: Construct
-Weighted-normalized decision matrix ($\tilde{R}_{ij}$)

Step 10: Calculate
-Positive ideal solution ($\tilde{r}_j^+$)
-Negative ideal solution($\tilde{r}_j^-$)

Step 11: Calculate
-Separation measures (S_i^+, S_i^-)

Step 12: Calculate
-Closeness coefficient ($C_i{}^+$)

Step 13: Rank
-Alternatives (A_i)

Figure 2. Schematic diagram of the proposed method.

4. Case Study

This section is cascaded into three subsections. Initially, the development of criteria for the evaluation of sustainable suppliers are presented through the review of extant literature and opinions of real experts from the industry. And then, a brief introduction on the background for an apparel industry example is provided using a real case from the city of Kahramanmaraş in Turkey. Numerical results and computational procedure are also included here as the last subsection. The identification of decision criteria to evaluate the given alternatives is the initial step in solving a MCDM problem.

Table 5. The evaluation criteria and their description

Criteria		Description
Ecological	(C_1)	This pillar stresses the importance of increasing awareness about environmental degradation [16,17].
Green Image	(C_{11})	This criterion represents the prioritization of environmental conservation [1,18].
Energy Consumption	(C_{12})	This criterion deals with the consumption of energy or power to contribute to more energy efficient processes [16,17].
Ecological Design	(C_{13})	This criterion refers how the entire product life cycle at the design stage is impacted environmentally [1,18].
Environmental Competencies	(C_{14})	This criterion handles the containment relationships balance capacity between economy and environment [15,19].
Pollution Control	(C_{15})	This criterion is a determining factor to work together by considering suppliers' attitude towards pollution [16,17].
Economical	(C_2)	This pillar expresses the overtime continuation of the wellbeing for the society [1,18].
Cost	(C_{21})	This criterion refers to Cost of acquisitioning product, including product, inventory, logistic [41].
Financial Status	(C_{23})	This criterion displays the actual ability of performing economic contracts. Good finances is key to improvement [41].
Quality	(C_{22})	This criterion is measured in terms of empathy, ease of communication, and blend of services provided [41].
Flexibility	(C_{24})	This criterion presents the ability of quick response to product demand variations [15,19].
Efficiency	(C_{25})	This criterion present the ability of fulfilling efficient orders within the given period of time [41].
Social	(C_3)	This pillar defines the security and diversity of supply within public acceptability.
Legal Responsibilities	(C_{31})	This criterion stresses the labor relations between workers and employers in the context of legal and human rights [16,17].
Privacy	(C_{32})	This criterion refers providing information to stakeholders in respecting the confidentiality [41].
Reputation	(C_{33})	This criterion stresses the keeping a good name among competitors in a long-term to gain competitive advantage [41].
Safety	(C_{34})	This criterion is concerned with the safety, health, and welfare of labor force [1,18].
Training	(C_{35})	This criterion deals with the process of enhancing the skills, capabilities, and knowledge of employees [15,19].

4.1. Sustainable supplier selection criteria

The goal in this sub-section is to determine the best available criteria for sustainable supplier selection through an extensive literature review and expert opinions. As far as the author know, the presented study is the first study to determine the sustainable supplier selection criteria in the context of social, environmental, and economical aspects. In today's competitive businesses, cost and quality are not enough to determine a suitable supplier due to the augmented consumer expectations. Hence, different evaluation criteria such as ecological, economical, and social criteria, have to be taken into account. Three main and 15 sub-criteria are defined based on the extant literature and through the extensive brainstorming of DMs. They are adapted to be used in the proposed methodology. Figure 1 presents the network structure of evaluation framework. Table 5 delivers the comprehensive description of the evaluation criteria.

4.2. Case background

The developed approach is applied to a textile factory established in Kahramanmaraş, Turkey. The name of the company is undisclosed due to confidentiality and privacy reasons. This factory is addressed as the Textile Company in this paper, hereafter. The factory is specialized in the production and development of innovative fabrics and technical yarns. This Textile Company has been established in 1989 having the first weaving mill of Kahramanmaraş, Turkey. Textile Company value partnerships with sustainable suppliers and apparel manufacturers as a supplier, end-user, and market-oriented factory. The competition in apparel industry is intense and it is a key distress for the Textile

Company to consider during its assessment of suppliers. Thus, the evaluation of the best sustainable supplier is an important decision-making process for the Textile Company.

A group of specialists consisting of three DMs, a chief textile engineer in Textile Company, a top-level manager of the Textile Company, and an academician having a considerable position in a Turkish university, are collaborated to pass judgment on six suppliers. The supplier selection procedure is a remarkable process in sustainability setting, recalling the existence of an obvious distinction between traditional supplier selection and sustainable supplier perspective. With the review of extensive literature and DMs' skills along with the managers of the Textile Company, each decision criterion is composed to evaluate and prioritize the presented candidates. The Textile Company intends to pick the finest alternative according to its expectations and needs. In the given study, six alternatives are assessed which the company intends to work together. The selected six alternatives are denoted by: A_1, A_2, A_3, A_4, A_5 and A_6 from now on.

4.3. Numerical application

Step 1: The given 6 alternatives are assessed by 3 main criteria and 15 sub-criteria set.

Step 2: A group consisting of 3 DMs are charged to evaluate the defined problem. Their individual weights are calculated by applying the Step 2 of the methodology. Table 6 presents the given individual evaluations of each DM and their respective weights.

Step 3: DMs' individual evaluation on each criterion is gathered in the form of verbal terms. The collected judgments are converted to PFSs values by applying Table 3. Due to space limitation and suitable appearance of the paper, the data is scaled. Thus, individual evaluation on main criteria in Table 7 is presented.

Table 6. The level of individual influence for each DM

DM	Preference			[$\mu_P(x)$,	$v_P(x)$]	λ_k
D_1	-	VI	MI	0.654	0.335	0.385
D_2	I	-	MI	0.585	0.397	0.336
D_3	MI	MI	-	0.500	0.450	0.279

Table 7. DMs' individual evaluation on main criteria

DM	C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3
D_1	EI	1/IV4	IV4	IV4	EI	1/IV4	1/IV4	IV4	EI
D_2	EI	1/VSI	IV4	VSI	EI	VSI	1/IV4	1/VSI	EI
D_3	EI	1/IV4	IV4	IV4	EI	IV3	1/IV4	1/IV3	EI

Step 4: Individual evaluations are fused together with PFWA aggregation operation in Eq. (11). The GDM matrix for the main criteria is presented in Table 8.

Step 5: CR is controlled for the aggregated PFSs matrix. The calculated CR values are smaller than 0.10 and so the judgment matrix is consistent.

Table 8. Aggregated pairwise matrix

Criterion	[$\mu_P(x)$,	$v_P(x)$]
C_1	0.597	0.507
C_2	0.567	0.514
C_3	0.647	0.474

Table 9. The PFSs criteria weights and crisp criteria weights

	$\widetilde{w}_j$			$\widetilde{w}_{jj}$		$\widetilde{w}_j \otimes \widetilde{w}_{jj}$			
Main	$[\mu_P(x),$	$v_P(x)]$	Sub	$[\mu_P(x),$	$v_P(x)$]	$[\mu_P(x),$	$v_P(x)]$	w_j	Rank
			(C_{11})	0.463	0.307	0.276	0.572	0.069	12
			(C_{12})	0.579	0.291	0.346	0.566	0.068	10
(C_1)	0.597	0.507	(C_{13})	0.607	0.302	0.362	0.570	0.067	9
			(C_{14})	0.628	0.405	0.375	0.615	0.062	1
			(C_{15})	0.568	0.396	0.339	0.611	0.064	4
			(C_{21})	0.558	0.393	0.317	0.614	0.064	5
			(C_{22})	0.597	0.395	0.338	0.616	0.063	3
(C_2)	0.567	0.514	(C_{23})	0.669	0.273	0.379	0.565	0.067	8
			(C_{24})	0.572	0.327	0.325	0.585	0.067	7
			(C_{25})	0.554	0.266	0.314	0.562	0.070	13
			(C_{31})	0.525	0.336	0.340	0.559	0.069	11
			(C_{32})	0.543	0.451	0.351	0.618	0.063	2
(C_3)	0.647	0.474	(C_{33})	0.650	0.346	0.421	0.563	0.065	6
			(C_{34})	0.577	0.254	0.373	0.524	0.071	15
			(C_{35})	0.630	0.241	0.408	0.519	0.070	14

Table 10. The individual linguistic evaluations of each DM

A_i	D_i	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}
	D_1	I	I	VU	U	VU	EU	EU	VU	VU	EU	VU	VU	I	EI	MI
A_1	D_2	MI	MI	VU	U	VU	I	U	EU	VU	U	I	EI	MI	MI	EI
	D_3	VI	MI	U	VU	U	EU	VU	U	I	VU	EU	VI	I	MI	MI
	D_1	VU	VU	I	EI	EI	VU	EI	EU	VU	EI	I	I	MI	I	EU
A_2	D_2	EU	U	VU	VI	EU	U	EI	VU	EU	VI	I	EI	EI	VI	EI
	D_3	VU	I	EU	MI	EI	I	VI	VU	EU	EI	EU	VI	EI	MI	VU
	D_1	EI	MI	VI	MI	I	EI	I	VU	EU	U	VU	U	EI	EI	EI
A_3	D_2	VI	MI	VU	I	U	MI	EI	VI	MI	VU	EU	I	VI	EI	I
	D_3	VI	I	U	VU	U	I	EI	EU	EI	VU	U	VU	VI	EI	I
	D_1	VU	VI	VU	EU	MI	VU	MI	U	VU	I	EI	VI	EU	VU	VU
A_4	D_2	U	I	U	EI	VU	EU	EI	U	EU	EU	MI	EI	I	MI	EU
	D_3	EI	U	VU	EU	EU	VU	I	VI	I	VU	VU	EI	VI	EI	EU
	D_1	U	U	VU	VU	EU	VU	EU	MI	EI	MI	VU	EU	I	MI	I
A_5	D_2	VU	VU	U	VU	U	I	U	VU	VU	VU	EU	VU	EI	MI	MI
	D_3	EU	I	EU	I	VU	EU	VU	EU	U	MI	EI	I	MI	EI	MI
	D_1	EU	I	EU	VU	U	I	VU	EU	U	EU	EU	MI	VU	EU	VI
A_6	D_2	EU	U	VU	EI	EI	VI	U	I	VU	I	VU	VU	VU	EU	VU
	D_3	VU	EU	U	EU	VU	VU	EI	VI	VI	MI	VI	MI	VU	U	I

Step 6: Each criterion weight ($\widetilde{w}_j$) is calculated using each DMs' judgments. Table 9 presents the PFSs criteria weights. In order to better visualize and grasp the priority of criteria on each other, Crisp AHP criteria weights are also created. Table 9 presents the crisp AHP criteria weights. The criterion C_{14} has the utmost priority while criterion C_{34} has the last.

Step 7: The individual judgments of DMs in the form of linguistic variables are converted by the use of Table 2 to form individual decision matrix. Table 10 presents the individual linguistic evaluations of each DM.

Step 8: The alternatives evaluated individually are fused into group opinion to set GDM matrix by PFWA aggregation operator. Table 11 presents the aggregated alternative evaluation matrix.

Step 9: The normalization of evaluation matrix is utilized by the Eq. (10) for each cost type criterion. The Eq. (17) is used to find weighted matrix. Each weight is given in Table 9. Apply PFSs multiplication operator to obtain the new weighted-normalized decision matrix as presented in Table 11.

Step 10: The positive (A^{+}) and negative (A^{-}) ideal solutions are calculated by the use of Eq. (18) and (19), respectively. Table 11 presents the positive and negative ideal solutions.

Step 11: separation measures of negative and positive ideal solutions are estimated by the use of Eq. (20) and (21) to calculate. Table 12 presents the calculated separation measures.

Step 12: The closeness coefficients for all alternatives are calculated by the use of Eq. (22). Table 12 presents the calculated closeness coefficient.

Table 11. The aggregated and weighted-normalized matrix of first alternative and respective positive and negative ideal solutions

	A_{1j}		$\widetilde{R}_{1j}$		A^{+}		A^{-}	
	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	μ_j^{+}	v_j^{+}	μ_j^{-}	v_j^{-}
C_{11}	0.80	0.19	0.22	0.65	0.22	0.65	0.05	0.92
C_{12}	0.55	0.40	0.14	0.81	0.19	0.76	0.12	0.85
C_{13}	0.56	0.46	0.20	0.77	0.20	0.77	0.09	0.89
C_{14}	0.52	0.47	0.19	0.80	0.28	0.70	0.12	0.87
C_{15}	0.50	0.50	0.17	0.81	0.26	0.71	0.09	0.90
C_{21}	0.72	0.26	0.08	0.89	0.24	0.70	0.08	0.89
C_{22}	0.80	0.19	0.27	0.69	0.28	0.68	0.09	0.90
C_{23}	0.52	0.53	0.20	0.80	0.22	0.75	0.08	0.90
C_{24}	0.61	0.38	0.20	0.74	0.21	0.74	0.06	0.92
C_{25}	0.29	0.70	0.09	0.87	0.26	0.63	0.08	0.89
C_{31}	0.26	0.73	0.09	0.88	0.23	0.71	0.09	0.88
C_{32}	0.47	0.54	0.17	0.82	0.29	0.68	0.14	0.85
C_{33}	0.80	0.19	0.34	0.65	0.34	0.65	0.11	0.89
C_{34}	0.85	0.14	0.32	0.59	0.32	0.59	0.09	0.89
C_{35}	0.75	0.24	0.31	0.63	0.31	0.63	0.08	0.91

Step 13: By applying a descending order for the closeness coefficient (C_i^{+}), the alternatives are ranked. Table 12 presents the ranking of alternatives. The result indicated that the best alternative in ranking is A_2 while the worst is A_6. The obtained outcome is also validated by the DMs as satisfactory.

$$A_6 < A_1 < A_5 < A_4 < A_3 < A_2$$

Table 12. The separation measure, closeness coefficient and ranking of alternatives

	S_i^{+}	S_i^{-}	C_i^{*}	Rank
A_1	0.715	0.653	0.477	5
A_2	0.548	0.797	0.592	1
A_3	0.569	0.784	0.579	2
A_4	0.633	0.732	0.536	3
A_5	0.703	0.665	0.486	4
A_6	0.742	0.622	0.456	6

5. Discussion and Analysis

Sustainability concept has raised a considerable attention in academic and industrial area, yet its meaning is not always clear. Sustainability may imply very different policy responses depending on its interpretation. The earliest sustainability studies on supply chain management can be traced back to the 90s, when the sustainability concept mainly discussed as environmental management [42]. Sustainability draws the line between socially responsible and irresponsible businesses. Sustainability has three goals known as the triple bottom line: people, planet, and profit. As the company can effect these three areas positively, it is considered more sustainable [2].

This study reports a novel MCDM method by combining the AHP technique with the TOPSIS technique under PFSs environment to evaluate the most suitable sustainable supplier. In the proposed method, the AHP technique is utilized to compute the optimal evaluation criteria weights; the TOPSIS technique is used to manage DMs' assessments on the alternative sustainable suppliers' performance and to generate the ranking orders of the sustainable supplier alternatives.

The AHP technique is a MCDM method developed by Thomas Saaty [40] in the 1970s. It is a quantitative method used to order and select alternatives with multiple criteria and multiple DMs under certain or uncertain decision environment. AHP allows modeling the hierarchical structure by representing the relationship among the main target of the problem, criteria, and sub-criteria for the complex problems of DMs. AHP technique reduces the complex decision problem (multiple alternative and multiple criteria) to pairwise comparisons, checks whether the comparisons are consistent, and tries to get an outcome.

The TOPSIS technique is a MCDM method developed by Hwang and Yoon in 1981 [5]. The presented approach has exploited the proposition hypothesizing the ideal candidate as the alternative having position very near position to positive ideal solution and very far from the negative ideal solution. The positive ideal solution considers the minimum of the cost criteria and the maximum of the benefit criteria. The negative ideal solution considers the maximum of the cost criteria and the minimum of the benefit criteria. Succinctly, the positive ideal solution considers the best value of the solution criteria while negative ideal solution considers the worst value of the solution criteria. This approach prioritizes the alternatives by considering distances from positive ideal to negative ideal solutions.

Decision-making is a large part of every-day life. If a decision is taken by only one person, making that decision is relatively easy since an individual can make a quicker decision than a group can. Individual decision-making, however, could create a prejudice and bias when compared to a group's involvement. Many important decisions are made with GDM, and recent literature demonstrates the systematic differences and strengths of GDM both experimentally and theoretically [10].

Yager recently introduced the PFSs theory [8,37] as an extension of IF set theory. Yager recently has showed that there may be some cases in which the sum of membership and non-membership (supporters + opponents > 1) of the opinion of a DM is greater than one in the real-world environment. This is not allowed in conventional theories because the sum is greater than one. According to PFSs theory, the sum of membership and non-membership can exceed one as long as the sum of squares does not exceed one. This property gives a higher flexibility and ability to express the uncertain and vague information compared to IF sets. Therefore, the PFSs theory have been applied to many MCDM problems. PFSs are more advantageous in imprecise and fuzzy modeling of objective world and can model and solve complex problems more adequately.

5.1 Comparison

The reliability and rationality of the obtained rankings by the proposed method is demonstrated by means of a comparative investigation. The similar supplier ranking evaluation is also completed by applying the following comparable MCDM approaches in PFSs environment: PF-VIKOR, PF-COPRAS, PF-TODIM. The rankings attained by these approaches are charted in Figure 3 for comparison. From this figure, it can be seen that the best ranked supplier and the worst ranked supplier are the same in the PF-VIKOR and PF-COPRAS MCDM methods, and the best ranked supplier of the proposed method is the second best in PF-TODIM. Thus, this demonstrates the strength and justification of the developed method. It is easily observable by looking at the given analysis that the outcome is an excellent match to each other and to the consequence of the obtained ranking order.

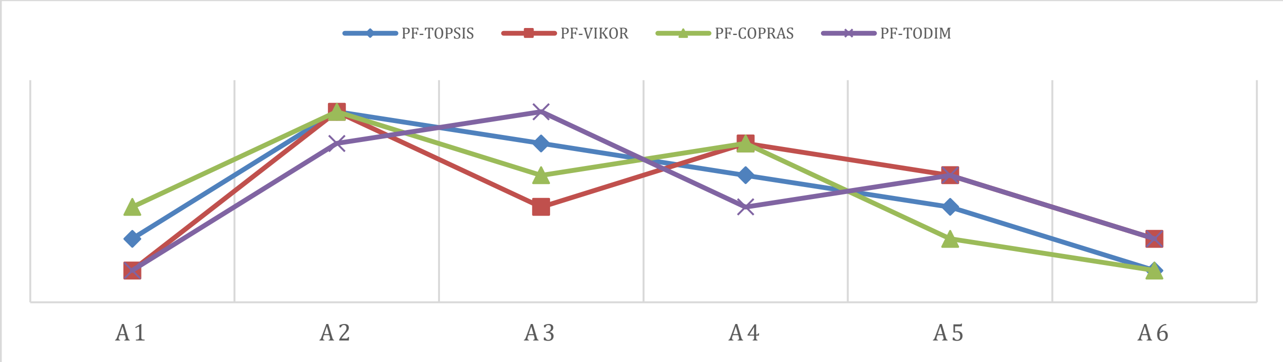

Figure 1. Comparison with existing methods

In order to create a link between the results obtained by the different approaches, Spearman's correlation coefficient is tested. The Spearman's correlation coefficient of ranks is a significant and convenient indicator to determine the connection among the obtained results [10]. Besides, the Spearman's correlation coefficient is suitable to use in case of ordinal or ranked variables, as is the case here. This technique is applied to test the statistical significance of the difference between the ranks. The results of The Spearman's correlation coefficient for the obtained ranks can be seen in Figure 4, which shows a high correlation among the MCDM approaches for the obtained ranks. All coefficient values are greater than 0.90 which shows a very high correlation. The result indicate that an extremely high closeness is exist within the proposed method and the existing PFSs methods for the handling of uncertainty. Based on the obtained results of ranking comparison and correlation check, it can be established that the attained rankings of the proposed method are robust and justifiable. In addition to credibility of the ranks, the method proposed can successfully exploits the hesitations that occur in GDM environment. The computations are not incorporated here since the section is only devoted to a comparative analysis of the attained final ranks

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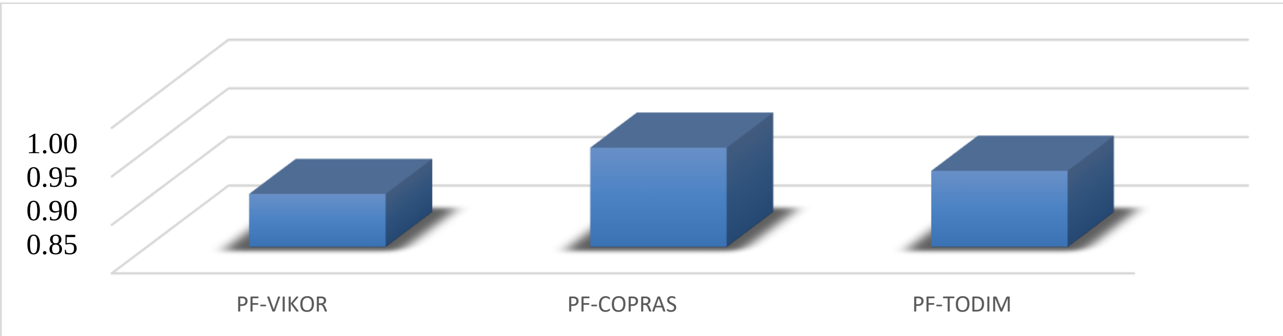

Figure 2. Spearman's correlation coefficient of ranks

5.2 Sensitivity analysis

The sensitivity analysis is carried out by changing the weight of one criterion at a time while keeping others unchanged. For example, the weight of criterion C_{11} is varied and given the PFSs value corresponding to the EI linguistic term, and subsequently, the weight of other criteria is also exchanged with the weight of EI. A total of 16 experiments are conducted and results are charted in Figure 5. Figure 5 represents variations in the final ranking of different supplier evaluations with the change of the criteria. Fifteen experiments of sensitivity analysis together with the base scenario of obtained outcome is depicted in Figure 5 shows that alternative A_2 is the best alternative among sustainable supplier alternatives for 10 scenarios and second best one for the rest. The ranking of other alternatives does not change considerably with the criteria's weight. This shows that the ranking of sustainable supplier alternative is sensitive to the weight of selected criteria.

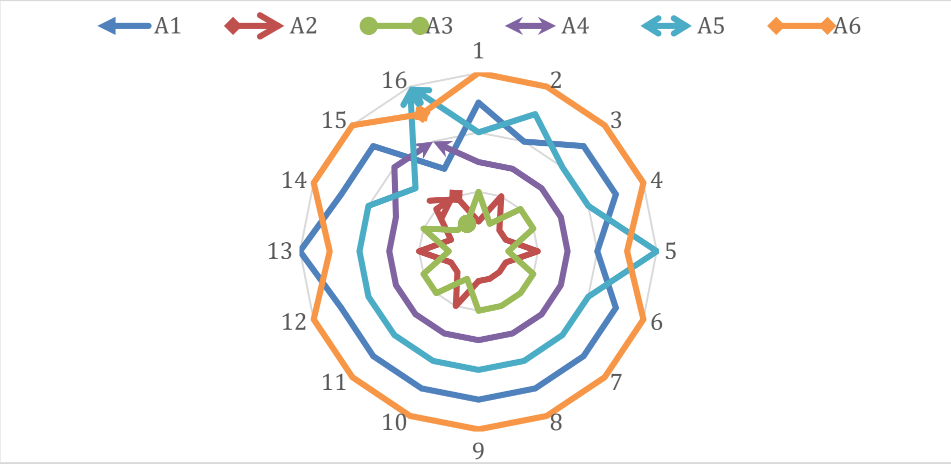

Fig. 3. Sensitivity Analysis

6. Conclusion

Sustainability has gained an increasing consideration among scholars and practitioners in the last several decades. Several different types of initiatives exist which aim to provide methods and tools for the supplier selection process in the context of sustainability assessment. The proposed MCDM methodology is built on the combination of AHP technique and TOPSIS method using PFSs setting for GDM environment. In the given methodology, the AHP method is applied to determine criterion weight and the TOPSIS method is applied to assess the candidates. Thus, the priority ranks are obtained for each alternative. The study provides a systematic decision approach in order to choose the logical candidate for sustainable suppliers. In addition, many DMs have a tendency to make use of linguistic expressions in stating their judgments as a result of ambiguous decision environment. This new methodology allows to capture the vagueness and hesitation associated with the DMs' judgments with the aid of PFSs' enhanced solution environment. Besides, the AHP technique can obtain the near optimal weights of criteria by constructing hierarchical evaluation structure. For the evaluation of supplier alternatives, The TOPSIS as a distance based, intuitive and reliable ranking technique can achieve a better result. Compared with the given approaches applied in the above comparative analysis section, the proposed approach has the distinct gains. The sensitivity analysis verifies the stability of the proposed method, which has benefit of reliability in decision-making process. Consequently, the proposed method is more preferable to the others for a range of GDM problems that deal with vague and subjective data. In order to determine the identification criteria for sustainable supplier selection, the available and relevant literature is examined. The developed main and sub criteria are stated to be the most relevant, which is confirmed by the DMs and the Textile Company and cover the widest aspects in comparison to the extant literature. Involving PFSs theory with MCDM approaches can conclude in far better reliable result due to DMs' opacity and fuzziness of information. The cohesive PFSs approach integrates the PFSs theory with AHP and TOPSIS, which can reach more consistent results. The obtained outcome justifies that the developed method is more capable to capture uncertainty and ambiguity of DMs' evaluations and it is further effective and efficient to derive the ranking orders of sustainable supplier alternatives.

The proposed method has the advantage of enabling a quick decision for supplier selection process. The limitation of the research can be the dependence to the DMs' experience and the quality of their judgments. The hierarchical inter-dependency and mutual relationships between main and sub criteria has not yet studied. The ANP technique can be used in future studies to enhance solution quality. Furthermore, the approach can also be applied by extending it to interval valued PFSs environments and the rationality could be verified in uncertain MCDM setting.

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Conflicts of interest

The author declare that he has no conflict of interest.

References

[1] Luthra S., Govindan K., Kannan D., Mangla S.K., Garg C.P., An integrated framework for sustainable supplier selection and evaluation in supply chains, *J. Clean. Prod.*, 140 (2017) 1686–1698.

[2] Büyüközkan G., Çifçi G., An integrated QFD framework with multiple formatted and incomplete preferences: A sustainable supply chain application, *Appl. Soft Comput. J.*, 13 (2013) 3931–3941.

[3] Brauers W.K.M., Zavadskas E.K., The MOORA method and its application to privatization in a transition economy, *Control Cybern.*, 35 (2006) 445–469.

[4] Saaty T.L., The analytic hierarchy process: planning, priority setting, resources allocation, McGraw-Hill. (1980).

[5] Hwang C.L., Yoon K., Multiple Attribute Decision Making-Methods and Application, New York: Springer, (1981).

[6] Zadeh L.A., Fuzzy sets, *Inf. Control.*, 8 (1965) 338–353.

[7] Atanassov K.., Intuitionistic fuzzy sets, *Fuzzy Sets Syst.*, 20 (1986) 87–96.

[8] Yager R.R., Abbasov A.M., Pythagorean Membership Grades, Complex Numbers, and Decision Making, *Int. J. Intell. Syst.*, 28 (2013) 436–452.

[9] Yager R.R., Pythagorean Membership Grades in Multicriteria Decision Making, *IEEE Trans. Fuzzy Syst.*, 22 (2014) 958–965.

[10] Büyüközkan G., Göçer F., Smart medical device selection based on intuitionistic fuzzy Choquet integral, *Soft Comput.*, 23 (2019) 10085–10103.

[11] Büyüközkan G., Göçer F., Karabulut Y., A new group decision making approach with IF AHP and IF VIKOR for selecting hazardous waste carriers, *Measurement.*, 134 (2019) 66–82.

[12] Büyüközkan G., Göçer F., A Novel Approach Integrating AHP and COPRAS Under Pythagorean Fuzzy Sets for Digital Supply Chain Partner Selection, *IEEE Trans. Eng. Manag.*, (2021) 1–18.

[13] Yucesan M., Gul M., Hospital service quality evaluation: an integrated model based on Pythagorean fuzzy AHP and fuzzy TOPSIS, *Soft Comput.*, 24 (2020) 3237–3255.

[14] Çalık A., A novel Pythagorean fuzzy AHP and fuzzy TOPSIS methodology for green supplier selection in the Industry 4.0 era, *Soft Comput.*, 24 (2020) 3237–3255.

[15] Liu H.-C., Quan M.-Y., Li Z., Wang Z.-L., A new integrated MCDM model for sustainable supplier selection under interval-valued intuitionistic uncertain linguistic environment, *Inf. Sci. (Ny)*. 486 (2019) 254–270.

[16] Zimmer K., Fröhling M., Schultmann F., Sustainable supplier management – a review of models supporting sustainable supplier selection, monitoring and development, *Int. J. Prod. Res*., 54 (2016) 1412–1442.

[17] Xu Z., Qin J., Liu J., Martínez L., Sustainable supplier selection based on AHPSort II in interval type-2 fuzzy environment, *Inf. Sci.*, 483 (2019) 273–293.

[18] Rabbani M., Foroozesh N., Mousavi S.M., Farrokhi-Asl H., Sustainable supplier selection by a new decision model based on interval-valued fuzzy sets and possibilistic statistical reference point systems under uncertainty, *Int. J. Syst. Sci. Oper. Logist.*, 6 (2019) 162–178.

[19] Abdel-Baset M., Chang V., Gamal A., Smarandache F., An integrated neutrosophic ANP and VIKOR method for achieving sustainable supplier selection: A case study in importing field, *Comput. Ind.*, 106 (2019) 94–110.

[20] Song Y., Li G., A large-scale group decision-making with incomplete multi-granular probabilistic linguistic term sets and its application in sustainable supplier selection, *J. Oper. Res. Soc.*, 70 (2019) 827–841.

[21] Pishchulov G., Trautrims A., Chesney T., S. Gold, L. Schwab, The Voting Analytic Hierarchy Process revisited: A revised method with application to sustainable supplier selection, *Int. J. Prod. Econ.*, 211 (2019) 166–179.

[22] Foroozesh N., Tavakkoli-Moghaddam R., Mousavi S.M., An interval-valued fuzzy statistical group decision making approach with new evaluating indices for sustainable supplier selection problem, *J. Intell. Fuzzy Syst.*, 36 (2019) 1855–1866.

[23] Ozdemir Y., Gul M., Measuring development levels of NUTS-2 regions in Turkey based on capabilities approach and multi-criteria decision-making, *Comput. Ind. Eng.*, 128 (2019) 150–169.

[24] Tepe S., Kaya İ., A fuzzy-based risk assessment model for evaluations of hazards with a real-case study, Hum. Ecol. Risk Assess. *An Int. J.*, (2019) 1–26.

[25] Gul M., Ak M.F., A comparative outline for quantifying risk ratings in occupational health and safety risk assessment, *J. Clean. Prod.*, 196 (2018) 653–664.

[26] Gul M., Application of Pythagorean fuzzy AHP and VIKOR methods in occupational health and safety risk assessment: the case of a gun and rifle barrel external surface oxidation and colouring unit, *Int. J. Occup. Saf. Ergon*., (2018) 1–14.

[27] Gul M., Guneri A.F., Nasirli S.M., A fuzzy-based model for risk assessment of routes in oil transportation, *Int. J. Environ. Sci. Technol.*, 16 (2019) 4671–4686.

[28] Zhang X., Xu Z., Extension of TOPSIS to Multiple Criteria Decision Making with Pythagorean Fuzzy Sets, *Int. J. Intell. Syst.*, 29 (2014) 1061–1078.

[29] Garg H., A New Improved Score Function of an Interval-Valued Pythagorean Fuzzy Set based TOPSIS Method, *Int. J. Uncertain. Quantif.*, 7 (2017) 463–474.

[30] Khan A., Abdullah S., Yousaf M.A., Hussain I., Farooq M., Extension of TOPSIS method base on Choquet integral under interval-valued Pythagorean fuzzy environment, *J. Intell. Fuzzy Syst.*, 34 (2018) 267–282.

[31] Liang D., Xu Z., The new extension of TOPSIS method for multiple criteria decision making with hesitant Pythagorean fuzzy sets, A*ppl., Soft Comput.*, 60 (2017) 167–179.

[32] Onar S.C., Oztaysi B., Kahraman C., Multicriteria Evaluation of Cloud Service Providers Using Pythagorean Fuzzy TOPSIS, *J. Mult. Log. Soft Comput*., 30 (2018) 263–283.

[33] Oz N.E., Mete S., Serin F., Gul M., Risk assessment for clearing and grading process of a natural gas pipeline project: An extended TOPSIS model with Pythagorean fuzzy sets for prioritizing hazards, Hum. Ecol. Risk Assess., *An Int. J.*, (2018) 1–18.

[34] Sajjad Ali Khan M., Ali A., Abdullah S., Amin F., Hussain F., New extension of TOPSIS method based on Pythagorean hesitant fuzzy sets with incomplete weight information, *J. Intell. Fuzzy Syst.*, 35 (2018) 5435–5448.

[35] Biswas A., Sarkar B., Pythagorean fuzzy TOPSIS for multicriteria group decision-making with unknown weight information through entropy measure, *Int. J. Intell. Syst.*, 34 (2019) 1108–1128.

[36] Wang L., Wang H., Xu Z., Ren Z., The interval-valued hesitant Pythagorean fuzzy set and its applications with extended TOPSIS and Choquet integral-based method, *Int. J. Intell. Syst.*, 34 (2019) 1063–1085.

[37] Yager R.R., Pythagorean fuzzy subsets, in: 2013 Jt. IFSA World Congr. NAFIPS Annu., *Meet., IEEE*, 2013: pp. 57–61.

[38] Peng X., Yang Y., Some Results for Pythagorean Fuzzy Sets, *Int. J. Intell. Syst.*, 30 (2015) 1133–1160.

[39] Abdullah L., Najib L., A new preference scale of intuitionistic fuzzy analytic hierarchy process in multi-criteria decision making problems., *J. Intell. Fuzzy Syst.*, 26 (2014) 1039–1049.

[40] Saaty T.L., A scaling method for priorities in hierarchical structures, *J. Math. Psychol.*, 15 (1977) 234–281.

[41] Feyzioğlu O., Göçer F., Büyüközkan G., Interval-valued intuitionistic fuzzy MULTIMOORA approach for new product development, in: Data Sci. Knowl. Eng. Sens. Decis. Support, World Scientific, (2018), 1066–1073.

[42] Büyüközkan G., Berkol Ç., Designing a sustainable supply chain using an integrated analytic network process and goal programming approach in quality function deployment, *Expert Syst. Appl.* 38 (2011) 13731–13748.