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Research Article

A Pythagorean Fuzzy Approach for Sustainable Supplier Selection Using TODIM

Prabjot Kaur[1], **Vaishnudebi Dutta**[1], **Bijay Lal Pradhan**[2], **Subhomoy Haldar**[1], **and Supriya Chauhan**[1]

[1]*Department of Mathematics, Birla Institute of Technology, Mesra, Ranchi, Jharkhand, India*
[2]*Department of Statistics, Amrit Campus, Tribhuvan University, Kathmandu, Nepal*

Correspondence should be addressed to Bijay Lal Pradhan; bijaya.pradhan@ac.tu.edu.np

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Several firms have become increasingly concerned with sustainability in recent decades and are thus implementing environmental and social changes in their businesses and supply networks. This article aims to assess suppliers based on green design, corporate social responsibility, energy consumption, and other sustainability factors that might aid the growth of a company. Characteristics used in this study will help to accomplish economic, environmental, and social responsibility for organizations to reduce global warming and natural resource depletion. We have used the data given in the article of Zolfani et al. by implementing Pythagorean fuzzy TODIM (an acronym in Portuguese for iterative multicriteria decision making) to calculate the rank of suppliers based on the Triple Bottom Line (TBL) sustainability framework. Both TODIM and PF-TODIM are simple to compute, stable, consistent, and accurate, but we have proved by calculations why Pythagorean fuzzy TODIM should be chosen over TODIM in such situations, where decision makers do not have access to a reliable data source. Finally, we performed a sensitivity analysis on both TODIM and PF-TODIM, and the results bolstered the utility of the model.

1. Introduction

In the management of a supply chain, supplier selection is critical. The goal is to find a supplier who can provide the finest product or service for the least amount of money. Proper supplier selection results in a high level of profit and quality. In this strategic partnership, the supplier is considered as an important part of the business. Selection of these suppliers has become more difficult because of the recent emphasis on sustainability. Studies on environmental protection, also known as studies related to sustainability, have grown significantly across the world. Because of the new focus on sustainability, finding these suppliers has grown increasingly challenging. Environmental studies, or studies on sustainability, have exploded in popularity across the world Lee et al. [1]. Consumer and client knowledge of sustainability has increased tremendously, affecting how goods and services are created and provided. As a result, the concept of a sustainable supply chain emerged, attracting academic and industrial interest from both public and private organisations studied by Büyükozkan and Çifçi [2]. There are several other related research articles based on supply chain such as those of Bhatia et al. [3], which enlighten us with Mehar approach for finding the shortest path in the supply chain network. [4]

One of the most crucial aspects of long-term supply chain management is supplier selection. Articles written by Büyükozkan and Çifçi [2], Nielsen et al. [5], and El Mariouli and Abouabdellah [6] include the coordination of all operations required in the management of the supply chain. As a result, instead of focusing on conventional criteria like cost, quality, or delivery, companies choose to focus on the “Triple Bottom Line” (TBL) approach for supplier assessment and selection. So, sustainability has become a term in the business world, and it is defined as development that satisfies current demands without jeopardising future generations' capacity to satisfy their own (WCED, 1987) [7]. When choosing sustainable suppliers, economic, environmental, and social aspects are all considered.

Many approaches for sustainable supplier selection have been developed because of the necessity of sustainable supply chain management. Thus, decision-supporting models can help a business achieve a competitive advantage as described in several articles, and some of them are those of Genovese et al. [8], Govindan et al. [9], Igarashi et al. [10], and Nielsen et al. [5]. Batista Schramm et al. [11] performed their research using popular databases, such as SCOPUS, to perform descriptive analytical studies. They discovered that when one strategy is applied individually, the most common ones are DEA (mathematical programming technique), TOPSIS, and AHP. The uncertainty of human-like knowledge in sustainability criteria is assessed using a mix of MCDM and fuzzy set theory in sustainable supplier selection. TOPSIS and fuzzy TOPSIS are the most commonly used MCDM methods; Shalke et al. [12], Mohammed [13], and Memari et al. [14] implemented fuzzy TOPSIS in their model to account for imprecision in judgments; Bai and Sarkis [15] did their analysis using TOPSIS with Grey Theory to deal with imprecision. They also shared research on the grey system and rough set technique. Bai and Sarkis [16] used Rough Set Theory to cope with uncertainties and imprecision, whereas Li et al. [17] used the Entropy Measure Method and Grey Correlation Study. dos Santos et al. [18] utilized a fuzzy approach of TOPSIS that aggregated Shannon's Entropy to introduce uncertainty to the study. Some of the other notable works include Luthra et al. [19], Jain and Singh [20], Zhao et al. [21], Jain et al. [22], Jain and Singh [23], and Qin et al. [24] where we see various MCDM approaches especially implemented in the substantiable supplier selection process.

Sarkis [25] used the analytical network process (ANP) to examine the influence of various organisational options on important environmentally conscious corporate practises. Galankashi et al. [26] used a fuzzy ANP method to choose green suppliers. For sustainable supplier selection and order allocation in the automobile sector, Khoshfetrat et al. [27] created a fuzzy, multiobjective, multiproduct, multiperiod mathematical model. Tavana et al. [28] used the ANP—QFD framework to solve the challenge of sustainable supplier selection, whereas Okwu and Tartibu [29] proposed a TOPSIS and ANFIS-based method to the problem of long-term supplier selection. Several other combined methods, such as fuzzy best worst method—fuzzy interference system (FBWM-FIS)—a hybrid fuzzy approach was used by Hoseini et al. [30] in Sustainable Supplier Selection (SSS) for construction industry, to simulate decision-making process for dealing with large number of criteria. Akman [31] utilised other MCDM techniques, such as VIKOR, while assessing suppliers to incorporate green supplier development plans using Fuzzy C Means. Almasi et al. [32] developed a multiobjective sustainable supplier selection and order allocation model that accounts for risk and inflation.

The findings of a TODIM (*TOmada de Deciso Interativa e Multicritério*—an acronym in Portuguese for iterative multicriteria decision making) MCDM technique are presented in this article. We utilised TODIM with Fuzzy Pythagorean Numbers to test both the findings and the rankings in a fuzzy environment, using the Rank Sum Method to calculate the weights of criteria. Authors like Gomes and Rangel [33] studied in their paper how the TODIM method constitutes efficient support for the evaluation of property. Mao et al. [34] used a hybrid method to assess a heterogeneous framework for sustainable supplier evaluation and selection, using interval-valued intuitionistic fuzzy TODIM (IVIF-TODIM). Khamesh [35] also looked at an integrated sustainable–flexible multicriteria model based on TODIM, which incorporated both gain and loss of decision and utilised prospect theory to account for uncertainty, whereas Bai et al. [36] used grey-BWM for attribute weights and grey TODIM to rank suppliers. From the perspective of sustainability, Table 1 contains a simplified list of publications where different MCDM methods were employed.

The data supplied to decision makers is not always clear or precise, due to which we depend on a fuzzy approach. The calculations and the methodology Pythagorean fuzzy TODIM shown in this article is not only accurate but also easier to grasp and compute than other methods such as improved TOPSIS studied by Tian et al. [37] or IF-TOPSIS studied by Memari et al. [14] or even IF-VIKOR studied by Abdel-Baset et al. [38]. We have also included the Python code at the conclusion of this article, which is freely accessible on our Github profile, so that researchers, academicians, and anybody else may use for their research purposes because sensitivity analysis software is not readily available. Theoretical contribution of our model is that we validated the PF-TODIM and shown through sensitivity analysis that it outperforms TODIM in riskier and more unpredictable environments for sustainable supplier selection. The Pythagorean Fuzzy method was selected because it may be considered a superset of the Triangular Fuzzy set, and the method is also relatable with the concept of intuitionistic fuzzy sets. This is the novelty of the Pythagorean Fuzzy method over the existing TODIM method. We selected the rank sum weight approach in our study because it provides decision makers greater flexibility in determining the relevance of criteria, and it is also easier to use and understand.

A case study of an Iranian steel company is used in our article to show the relevance and suitability of the recommended sustainability decision framework. Our aim is to answer the following in this article:

(1) What is the application of Pythagorean fuzzy TODIM?
(2) Why is TODIM in fuzzy environments more promising than TODIM on crisp sets?
(3) How sure can decision makers be about the ranks of the alternatives?

Table 1: Literature on multicriteria decision-making (MCDM) application based on sustainability perspective.

Publications	Methods used
Bojković et al. [39]	Modified ELECTRE
Majdi [40]	PROMETHEE and ELECTRE
Guo and Zhao [41]	Fuzzy TOPSIS
Micale et al. [42]	ELECTRE III
Awasthi et al. [43]	Fuzzy AHP-VIKOR
Chen and Ren [44]	Fuzzy ANP and fuzzy grey relational analysis
Suganthi [45]	Integrated fuzzy AHP, VIKOR/DEA
Wang et al. [46]	Hybrid fuzzy AHP
Nilashi et al. [47]	Hybrid TOPSIS—neuro fuzzy environment
Tang et al. [48]	Modified TOPSIS based on grey relational analysis
Du et al. [49]	Intuition fuzzy AHP-TODIM
Peng et al. [50]	Fuzzy exponential entropy, and extended VIKOR
Wu et al. [51]	DEMATEL-entropy TODIM
Alimohammadlou and Khoshsepehr [52]	Interval-valued intuitionistic fuzzy AHP and WASPAS
Tang et al. [53]	Fuzzy decision-making framework based on full consistency method and fusion ranking model

(4) What are the future scopes and how the researchers can be benefited?

All the abovementioned questions are answered in this article following the implementation of the model, sensitivity analysis, and discussion of future research possibilities.

2. Preliminaries

2.1. Pythagorean Fuzzy Sets and Pythagorean Fuzzy Numbers. The concept of Pythagorean fuzzy sets (PFS) was pioneered by Yager [54], to deal with vagueness with the membership grades as pairs satisfying the conditions of membership and nonmembership degree. We refer to Ren and Gou [55] for the definitions used and properties listed.

Let a set X be a universal set, then the PFS P is a mathematical object defined as

$$P = \left\{ \langle x, P\left(\mu_p(x), \nu_p(x)\right)\rangle | x \in X, 0 \leq \left(\mu_p(x)\right)^2 + \left(\nu_p(x)\right)^2 \leq 1 \right\}, \tag{1}$$

where μ_p represents the degree of membership and ν_p represents the degree of nonmembership of x in P. For the ease of using in programming applications, the definition of a Pythagorean Fuzzy Number (PFN) is

$$\beta = P\left(\mu_\beta, \nu_\beta\right), \tag{2}$$

where $\mu_\beta, \nu_\beta \in [0,1]$ and $\mu_\beta^2 + \nu_\beta^2 \leq 1$.

2.2. Operations on PFNs and Additional Functions. Besides μ_p and ν_p, PFNs have the following properties:

(1) Hesitant degree: $\pi_\beta = \sqrt{1 - \mu_\beta^2 - \nu_\beta^2}$.

(2) Score value: $s(\beta) = \mu_\beta^2 - \nu_\beta^2$.

(3) Accuracy value: $h(\beta) = \mu_\beta^2 + \nu_\beta^2$.

(4) Euclidean distance between two PFNs β_1 and β_2:

$$d(\beta_1, \beta_2) = \sqrt{\frac{1}{2}\left(\left(\mu_{\beta_1}^2 - \mu_{\beta_2}^2\right)^2 + \left(\nu_{\beta_1}^2 - \nu_{\beta_2}^2\right)^2 + \left(\pi_{\beta_1}^2 - \pi_{\beta_2}^2\right)^2\right)}. \tag{3}$$

The relevant mathematical operations (among others) on PFNs are as follows:

(1) Negation or complement $\beta^c = P(\nu_p, \mu_p)$

(2) Comparison of two PFNs β_1 and β_2 defined in the following manner:

(i) If $s(\beta_1) < s(\beta_2)$, then $\beta_1 < \beta_2$ (and vice versa)

(ii) If $s(\beta_1) = s(\beta_2)$, then
If $h(\beta_1) < h(\beta_2)$, then $\beta_1 < \beta_2$
If $h(\beta_1) = h(\beta_2)$, then $\beta_1 = \beta_2$
If $h(\beta_1) > h(\beta_2)$, then $\beta_1 > \beta_2$

3. Methodology for Solving Sustainable Supplier Selection Problem

3.1. The TODIM Method. The traditional TODIM algorithm, based on crisp numbers, is based on nonlinear CPT (Cumulative Prospect Theory) because its value function is identical to Tversky and Kahneman [56] CPT gain/loss function. Gains and losses are always calculated in relation to a reference point in this situation. As a result, although this method recognizes the possibility of decision makers, it does not account for their actual participation.

We start with the ratings as crisp (regular, nonfuzzy) numbers in the matrix $(x_{ij})_{m\times n}$. The alternatives are A_i, the criteria are C_j. Here, $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$.

Step 1: we normalize the ratings and weights using the formula:

$$P_{ij} = \begin{cases} \dfrac{x_{ij}}{\sum_{k=1}^{m} x_{kj}}, & \text{if } j \in J_1, \\ \\ \dfrac{\left(1/x_{ij}\right)}{\sum_{k=1}^{m}\left(1/x_{kj}\right)}, & \text{if } j \in J_2. \end{cases} \tag{4}$$

For the weighting factor or trade-off rate between the reference criteria r and the generic criteria c. In this case, w_r determines the most relevant reference criterion for the decision maker. Often, is it the maximum weight. In general, any criterion can be used as the reference criterion, and this decision has no effect on the final findings. So, the formula we have

$$w_{rc} = \frac{w_c}{w_r}, \tag{5}$$

where $w_r = \max\{w_c | c = 1, 2, \ldots, n\}$ and $i = 1, 2 \ldots, m$; $j = 1, 2 \ldots, n$.

Step 2: for calculating the dominance degree, we need to first check the contribution of each criteria using the formula, where φ_c is the contribution of criterion c to the function $\delta(A_i, A_j)$ and θ is the loss of attenuation factor whose value, we considered as 2.5 in our case. The value is chosen so because it is the median value in the range $(0, 5]$. Too small a value increases the sensitivity, whereas too big a value reduces the sensitivity. We perform further sensitivity analysis later on.

$$\varphi_c(A_i, A_j) = \begin{cases} \sqrt{\dfrac{(P_{ic} - P_{jc}) w_{rc}}{\sum_{c=1}^{n} w_{rc}}}, & \text{if } P_{ic} - P_{jc} \geq 0, \\ -\dfrac{1}{\theta}\sqrt{\dfrac{(\sum_{c=1}^{n} w_{rc})(P_{jc} - P_{ic})}{w_{rc}}}, & \text{if } P_{ic} - P_{jc} < 0. \end{cases} \tag{6}$$

Combining all contributions, we get the dominance degrees from the measurement of dominance $\delta(A_i, A_j)$ as

$$\delta(A_i, A_j) = \sum_{c=1}^{n} \varphi_c(A_i, A_j), \tag{7}$$

where $i, j = 1, 2 \ldots, m$; $c = 1, 2 \ldots, n$.

Step 3: finally, compute the values of ξ_i, which are the normalised global performances of alternatives in comparison to others, such that the largest value is picked as more significant than the value of other alternatives:

$$\xi_i = \frac{\sum_{j=1}^{n} \delta(A_i, A_j) - \min_i \sum_{j=1}^{n} \delta(A_i, A_j)}{\max_i \sum_{j=1}^{n} \delta(A_i, A_j) - \min_i \sum_{j=1}^{n} \delta(A_i, A_j)}, \tag{8}$$

where $i = 1, 2, \ldots, n$.

3.2. Pythagorean Fuzzy TODIM. In contrast to the normal version, the decision matrix is represented as $R = (r_{ij})_{m\times n}$.

$$R = \begin{bmatrix} P(\mu_{11}, \nu_{11}) & P(\mu_{12}, \nu_{12}) & \cdots & P(\mu_{1n}, \nu_{1n}) \\ P(\mu_{21}, \nu_{21}) & P(\mu_{22}, \nu_{22}) & \cdots & P(\mu_{2n}, \nu_{2n}) \\ \vdots & \vdots & \cdots & \vdots \\ P(\mu_{m1}, \nu_{m1}) & P(\mu_{m2}, \nu_{m2}) & \cdots & P(\mu_{mn}, \nu_{mn}) \end{bmatrix}, \tag{9}$$

where criteria are along the row and alternatives along the column. We follow the steps as follows:

Step 1: we create a Pythagorean decision fuzzy matrix $R = (r_{ij})_{m\times n}$, given by the decision maker.

Step 2: we convert this decision matrix into a normalized decision matrix $L = (l_{ij})_{m\times n}$ as

$$l_{ij} = \begin{cases} r_{ij}, & j \in J_1, \\ (r_{ij})^c, & j \in J_2, \end{cases} \tag{10}$$

where r_{ij} is for benefit criteria and $(r_{ij})^c$ is for the cost criteria.

Step 3: we then compute the relative weight of each criterion as $w_{jr} = w_j / w_r$, where w_j is the weight of criteria C_j and $w_r = \max\{w_j | j = 1, 2, \ldots, n\}$.

Step 4: the degree of dominance of each alternative A_i is then calculated over A_j with respect to criterion C_j by

$$\varphi_c(A_i, A_j) = \begin{cases} \sqrt{\dfrac{d(l_{ic}, l_{cj}) w_{rc}}{\sum_{c=1}^{n} w_{rc}}}, & \text{if } P_{ic} \geq P_{jc}, \\ -\dfrac{1}{\theta}\sqrt{\dfrac{(\sum_{c=1}^{n} w_{rc}) d(l_{ic}, l_{cj})}{w_{rc}}}, & \text{if } P_{ic} < P_{jc}, \end{cases} \tag{11}$$

where θ is the loss attenuation factor and $d(l_{ic}, l_{cj})$ is the distance between the PFN l_{ic} andl_{cj}.

Step 5: we then compute the overall dominance degree using formula (7):

$$\delta(A_i, A_j) = \sum_{c=1}^{n} \varphi_c(A_i, A_j). \tag{12}$$

Step 6: we then determine the overall value of each alternative A_i by formula (8)

$$\xi_i = \frac{\sum_{j=1}^{m} \delta(A_i, A_j) - \min_i\left\{\sum_{j=1}^{m} \delta(A_i, A_j)\right\}}{\max_i\left\{\sum_{j=1}^{m} \delta(A_i, A_j)\right\} - \min_i\left\{\sum_{j=1}^{m} \delta(A_i, A_j)\right\}}. \tag{13}$$

Each alternative may be ranked according to the notion, that is, the more the overall value ξ_i, the better the alternative A_i.

Step 7: the alternatives are then ranked based on their overall values.

3.3. Rank Sum Weighting Algorithm. Zoraghi et al. [57] said that the subjective method establishes weights solely based on the decision makers' considerations or judgments. It may be easier to describe alternative inexact weights, such as bounded weights, by ranking order the significance of criteria. Time constraints, the nature of the criterion, a lack of expertise, inaccurate, incomplete, or partial data, and the decision maker's limited attention and information processing abilities, for example, are all variables to consider. Because a group of decision makers may not agree on a set of specific weights, as Roszkowska [58] indicates, it may be reasonable to assume agreement on a weight ranking. This approach includes two steps: first, rating the criteria by significance and then weighting the criteria using the formula. The rank sum weight technique, which we used in our research, was proposed by Stillwell et al. [59]. In the rank sum (RS) approach, individual ranks are normalized by dividing the total of the rankings. The weights are calculated using the following formula:

$$w_j(RS) = \frac{2(n + 1 - r_j)}{n(n + 1)}, \tag{14}$$

where r_j is the rank of the jth criteria, $j = 1, 2, \ldots, n$.

4. Numerical Example

A Supplier Selection dataset for Alborz company in Iran is taken from Zolfani et al. [4]. The criteria for the evaluation are presented in Table 2. The crisp dataset of scores for the alternatives is presented in Table 3. The data comprise six suppliers being evaluated on seven criteria. We apply TODIM for the evaluation and selection of suppliers. For Pythagorean fuzzy TODIM, we make use of the modified data presented in Table 4.

Table 2: The criteria used for evaluation, their ranks, and weights.

Criteria	Name	Rank	Ideally	Weights
Price	Price	3	Lower	0.178571
Quality	Quality	5	Higher	0.107143
EC	Energy consumption	2	Lower	0.214286
GD	Green design	1	Higher	0.250000
DS	Delivery speed	6	Higher	0.071429
CSR	Corporate social responsibility	4	Higher	0.142857
EE	Employee education	7	Higher	0.035714

Table 3: Crisp scores for alternatives.

Name	Price	Quality	EC	GD	DS	CSR	EE
*S*1	10	4	8	10	2	0.7	8
*S*2	4	2	6	8	2	0.75	6
*S*3	1	1	8	6	2	0.65	6
*S*4	10	10	8	10	8	0.85	8
*S*5	2	4	6	6	2	0.75	6
*S*6	10	6	8	8	8	0.85	8

4.1. Regular TODIM

(1) First, we normalise the data we have on the suppliers. We also renormalise the weights.

(2) Next, we compare each pair (A_i, A_j) with respect to all criteria, keeping in mind the attenuation factor $\theta = 2.5$ to generate the ϕ values.

(3) We congregate the ϕ values for every category to calculate the δ values for each pair. The calculated δ matrix is shown in Table 5.

(4) We make use of the δ values to generate the ξ_i value for each alternative A_i, which are listed in Table 6.

(5) We rank the alternatives based on the ξ_i values, in decreasing order of preference.

Therefore, ranking the candidates using normal TODIM, we get

$$S_4 > S_6 > S_1 > S_5 > S_2 > S_3. \tag{15}$$

4.2. Pythagorean Fuzzy TODIM

(1) We consider the fuzzy responses of the decision makers on the scores of each alternative on every criterion and convert them to normalised Pythagorean Fuzzy Numbers.

(2) We take the complement of a PFN if the criterion is unfavourable.

(3) The weights are normalised. We can reuse the weights we calculated in the previous section.

(4) We generate the ϕ values for every pair and very criteria.

(5) We use the ϕ values to calculate the dominance degrees δ for all the pairs, which are displayed in Table 7.

(6) Using the δ values we calculate the rating ξ_i, listed in Table 8.

Table 4: Fuzzy scores for alternatives.

Name	Price	Quality	EC	GD	DS	CSR	EE
*S*1	(0.085, 0.01)	(0.68, 0.08)	(0.6375, 0.075)	(0.8, 0.1)	(0.2125, 0.025)	(0.7, 0.08)	(0.85, 0.1)
*S*2	(0.2125, 0.025)	(0.17, 0.02)	(0.85, 0.1)	(0.64, 0.08)	(0.2125, 0.025)	(0.75, 0.08)	(0.6375, 0.075)
*S*3	(0.85, 0.1)	(0.085, 0.01)	(0.6375, 0.075)	(0.51, 0.06)	(0.2125, 0.025)	(0.65, 0.076)	(0.6375, 0.075)
*S*4	(0.085, 0.01)	(0.85, 0.1)	(0.6375, 0.075)	(0.85, 0.1)	(0.8, 0.1)	(0.85, 0.1)	(0.85, 0.1)
*S*5	(0.425, 0.05)	(0.34, 0.04)	(0.85, 0.1)	(0.51, 0.06)	(0.2125, 0.025)	(0.75, 0.08)	(0.6375, 0.075)
*S*6	(0.065, 0.01)	(0.51, 0.061)	(0.6375, 0.075)	(0.68, 0.08)	(0.85, 0.1)	(0.85, 0.1)	(0.85, 0.1)

Table 5: δ matrix for regular TODIM.

	*S*1	*S*2	*S*3	*S*4	*S*5	*S*6
*S*1	0.000000	−0.327819	−0.292882	−1.516551	−0.536707	−1.171015
*S*2	−0.700333	0.000000	−0.247943	−1.977770	−0.561087	−1.619643
*S*3	−0.931105	−0.492989	0.000000	−2.088571	−0.548755	−1.841270
*S*4	0.356560	0.061872	−0.039756	0.000000	−0.081800	0.228050
*S*5	−0.363026	0.073358	−0.198827	−1.883937	0.000000	−1.572823
*S*6	0.128045	−0.092376	−0.130155	−0.633655	−0.189292	0.000000

Table 6: Ratings using regular TODIM.

	ξ_i
*S*1	0.320137
*S*2	0.123827
*S*3	0.000000
*S*4	1.000000
*S*5	0.304535
*S*6	0.775600

(7) Finally, we generate the ranking of the alternatives using the ratings. They are listed in descending order of preference.

The rankings using Pythagorean fuzzy TODIM are

$$S_4 > S_6 > S_1 > S_2 > S_5 > S_3. \quad (16)$$

Supplier 4 (*S*4) is the best supplier among the others, whereas Supplier 3 (*S*3) is the poorest pick, according to the computed results of both TODIM as well as PF-TODIM. This can be interpreted as *S*4 has the best quality, as well as the highest values for sustainable criteria, including Green Design, CSR, and staff education.

5. Sensitivity Analysis

The sensitivity analysis in this article is done for both TODIM and Pythagorean fuzzy TODIM, which reveals the effects and stability of each of the methods. In this study, the criteria weights are calculated using rank sum weight method. To see how sensitive the system is, we performed our study on the modification of the attenuation factor θ as studied by Ren and Gou [55] and by Li et al. [60] who did their sensitivity analysis by taking randomly selected six different values of attenuation factor. We also tested sensitivity of our model by rearranging the weights for each criterion and thereby rearranging the rank of the criteria we utilized in the rank sum weight approach. We analysed how weight adjustments can impact the rankings on our model when decision makers provide their choice of ranks while calculating the criteria weights. The sensitivity is displayed using the heatmap representation approach. We have around a 1000 data points for each test performed. This large amount of data cannot be effectively summarised by bar charts. Therefore, heatmaps are chosen as an effective means of conveying the essential information collected through the experiment at a glance. The ranks that appear more frequently in this scheme are darker in color than the ranks that appear less frequently, which are lighter in color. Black is the darkest color or color of most frequently occurring ranks, whereas white is the lightest, that is, no occurrence of rank has taken place.

Figures 1 and 2 show how sensitive the model would be if TODIM for crisp sets had been used instead of Pythagorean fuzzy TODIM. Figure 1 depicts a change in ranking for three of the alternatives, namely *S*1, *S*3, and *S*5, because of a change in attenuation factor. The rankings for the other three options, on the other hand, remain unchanged. Due to change in criteria weight, Figure 2 illustrates a change in rank for the same alternatives from Figure 1. Consequently, Supplier 4 (*S*4) is the most sustainable supplier, whereas Supplier 2 (*S*2) is the least sustainable of all.

As can be seen from the heatmap representation in Figures 3 and 4, the sensitivity analysis for Pythagorean fuzzy TODIM is stable. Changing the attenuation factor from 1 to 100 with a step size of 0.1 results in a total of 1001 observations with no change in rank for any of the alternatives. This indicates that the model is relatively stable and less susceptible to parameter (attenuation factor θ) changes. As a result, decision makers, and other stakeholders may depend on the ranking we established for suppliers using Pythagorean fuzzy TODIM. Moving to Figure 4, we have checked the change in ranks of the alternatives with change in criteria weights. Also, we can observe that only for the alternatives *S*3 and *S*5, there are light grey dots, which means at the rank 5 and rank 6, where the grey dots appear, the alternatives have shown change for a certain changed weight shuffle. The frequency of these new positions is negligible

Table 7: δ matrix for fuzzy TODIM.

	$S1$	$S2$	$S3$	$S4$	$S5$	$S6$
$S1$	0.000000	0.622632	1.094783	−2.526386	0.762338	−1.440690
$S2$	−2.957800	0.000000	0.245667	−4.921384	−0.010759	−4.309130
$S3$	−3.595614	−1.408338	0.000000	−5.321140	−1.238177	−4.794761
$S4$	0.701042	1.363427	1.498947	0.000000	1.500441	−0.002496
$S5$	−3.192777	−0.563682	0.074355	−5.163070	0.000000	−4.569714
$S6$	−0.463511	1.099182	1.285355	−1.143332	1.269214	0.000000

Table 8: Ratings using fuzzy TODIM.

	ξ_i
$S1$	0.694264
$S2$	0.205637
$S3$	0.000000
$S4$	1.000000
$S5$	0.137406
$S6$	0.859265

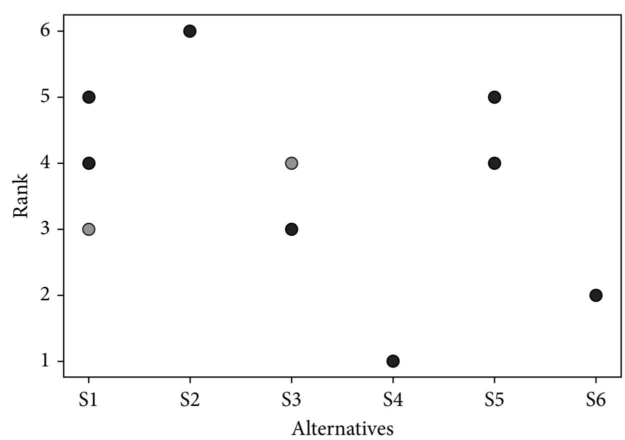

Figure 1: Rankings heatmap for regular TODIM by varying θ.

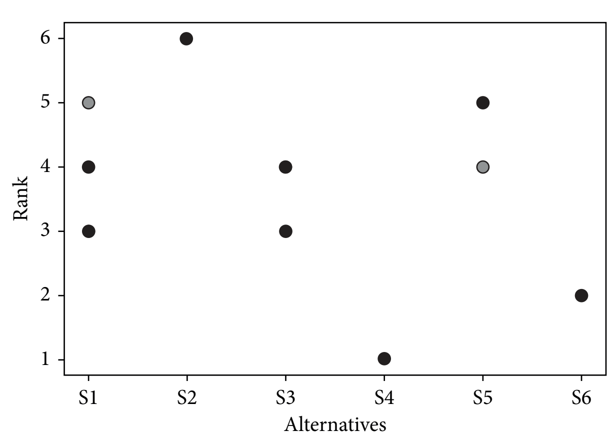

Figure 2: Rankings heatmap for regular TODIM by shuffling weights.

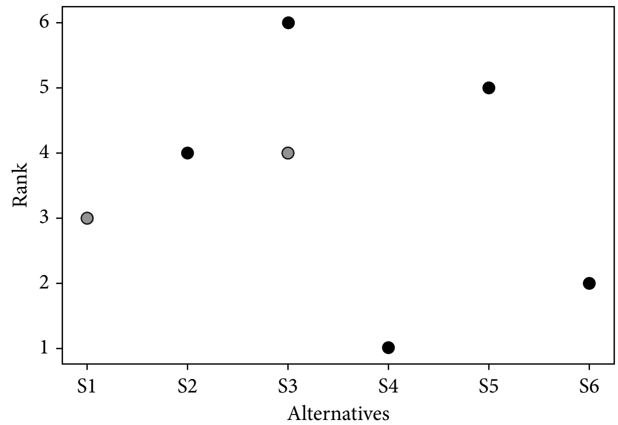

FIGURE 3: Rankings heatmap for fuzzy TODIM by varying θ.

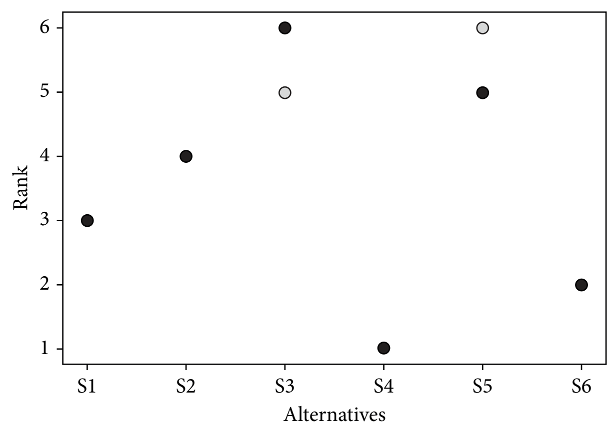

FIGURE 4: Rankings heatmap for fuzzy TODIM by shuffling weights.

compared with the main ranks due to their color being much lighter. The final rankings of PF-TODIM are a bit more dependable and resilient than TODIM for crisp set, as proved by sensitivity analysis. As a result, decision makers should rely on the PF-TODIM rankings.

6. Conclusion

As we have noted, according to the computed findings of both TODIM and PF-TODIM, Supplier 4 ($S4$) is the best supplier among the others, whereas Supplier 3 ($S3$) is the worst choice. $S4$ has the greatest quality as well as the highest values for sustainable criteria, such as Green Design, CSR, and employee education. The sensitivity analysis showed that among roughly 1000 observations, the position of the best supplier does not vary with change in values of parameter (attenuation factor θ) or weights of the criterion, demonstrating how consistent and reliable our model is. The list of rankings generated by varying θ and shuffling weights is available in the GitHub repository linked in the Supplementary Section. (Available here)

7. Discussion and Future Scope

Data studied in this article are acquired from Zolfani et al. [4] where they ranked the alternatives using Best Worst Method (BWM) and Combined Comprise Solution (CoCoSo) approach. After the application of the dataset in a fuzzy environment, which in our case is Pythagorean fuzzy TODIM, we have derived a different yet more stable and consistent result. The use of BWM has increased dramatically in a variety of sectors, including supplier selection and development as demonstrated by Rezaei et al. [61]. However, as Liang et al. [62] stated in their article, output-based consistency measurement in BWM cannot provide immediate feedback to a DM (decision maker), and only informs the DM about any inconsistencies in their assessments after the entire elicitation process has completed, which has been proven ineffective. As a result, we implemented the rank sum weight approach, which in general allows the decision maker with greater freedom in ranking the sustainability criteria for calculating the weights. We tested the sensitivity of our model to see how it would react if the order of the criteria changed. However, as seen in Figures 3 and 4, there is no discernible change in alternative rankings. We were inspired to make use of heatmap from an article by Yu et al. [63]. Also, we have not found any prior usages of heatmaps for sensitivity analysis especially in MCDM methods. We found the existing practice of using bar or line graphs to be inadequate. Therefore, in order to fulfil our requirements of conveying the results effectively, we have implemented heatmap.

Since 1997, decision support models in SSM or SSS have attracted a lot of attention in academics; however, there are still a lot of obstacles to overcome. Pythagorean fuzzy TODIM or PF-TODIM can be applied to places where decision makers are unsure about the data and can be implemented on various fields as Zimmer et al. [64] highlighted in industry-specific studies and comparisons, a comparison of widely used and seldom used modelling techniques, and the supplier qualifying process and transition to the final decision. Because of the simplicity of the computations, researchers may apply PF-TODIM to a variety of different disciplines, such as risk prediction in economic aspects of sports organisations or in aspect of sustainable sports tourism studied by Yang et al. [65]. In the article of Kumar et al. [66], we can find some of the widely used MCDM approaches in sustainable, renewable, energy development, such as TOPSIS, VIKOR, PROMETHEE, and ELECTRE, which can be further compared with TODIM and PF-TODIM, to check the superiority of our model with respect to stability. Recent research by Ecer [67] focused on performance evaluation of battery electric cars included many MCDM algorithms, such as MARCOS, COCOSO, and others. TODIM or PF-TODIM may be used in such datasets, and further studies can be done to compare these MCDM methods to TODIM and perform sensitivity analysis.

Two important limitations of our model, that is PF-TODIM, can be noted as follows:

(1) TODIM and its extensions, such as PF-TODIM, have higher time complexity for comparison, $O(mn^2)$ where m is the number of criteria and n is the number of candidates, whereas there exist other MCDM algorithms, such as TOPSIS, and its variants where the time complexity is relatively lower than TODIM.

(2) Although our model has a rank reversal problem, TODIM does not show a significant change in ranks when alternatives are added or deleted. According to some of our calculated observations, at most, two of the ranks are exchanged in this model. This is the limit. There may be situations, or for some dataset, we do not even have to deal with rank reversal, making our approach more reliable. However, additional research should be done to see whether this issue can be completely eliminated from the model, which would increase its overall value.

Data Availability

The Python source code along with the intermediate steps is available at the repository https://github.com/hungrybluedev/SustainabliltyFuzzyPTODIM.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Supplementary Materials

The Python source code along with the intermediate steps is available at the repository https://github.com/hungrybluedev/SustainabliltyFuzzyPTODIM. We have also provided the output generated by the Python code formatted into a single PDF file that includes all of the intermediate steps of the computation. The order in which the code and results are presented in the document is as follows: (1) TODIM ranking and (2) Pythagorean fuzzy TODIM ranking. (*Supplementary Materials*)

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