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A Heterogeneous MCDM Framework for Sustainable Supplier Evaluation and Selection Based on the IVIF-TODIM Method

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Abstract: The third-party platform named ECO system is used by many transnational companies to monitor the sustainability performance of their global suppliers because of its easiness and shareability. Nonetheless, methods used in this platform for evaluating and calculating the sustainability performance of the alternative suppliers are criticized for their lack of accuracy. In response to these problems, this paper presents a heterogeneous multi-criteria decision-making (MCDM) method based on interval-valued intuitionistic fuzzy–an acronym in Portuguese for interactive multi-criteria decision making (IVIF–TODIM) to improve the efficiency of the evaluation model. Considering the varying features of evaluation criteria, i.e., either quantitative or qualitative, the evaluation values under different criteria are expressed in their appropriate information types. In this paper, a general method based on the relative closeness to the technique for order preference by similarity to ideal solution (TOPSIS) method is applied for aggregating the heterogeneous assessment information, including crisp numbers, interval numbers, and triangular fuzzy numbers (TFNs), into interval-valued intuitionistic fuzzy numbers (IVIFNs). Then, the TODIM (an acronym in Portuguese for interactive multi-criteria decision making) is extended and employed to prioritize the alternative suppliers. Finally, the applicability and effectiveness of the proposed method is verified by a practical example of polymer manufacturing company and a comparison analysis with existing methods.

Keywords: sustainability; sustainable supplier selection; heterogeneous information; interval-valued intuitionistic fuzzy numbers; TODIM method

1. Introduction

Faced with environmental pollution, resource starvation, and the intensification of competition, sustainable development has been considered as a consensus among countries, organizations, and academic institutions [1]. More and more corporations have also realized that their value is highly related to the value of the supply chain network they have created, and therefore have started to modify their strategic and operational policies to improve the environmental performance of the products and the overall manufacturing processes from procurement of products to the delivery of finished goods [2]. The sustainability of the product not only includes the sustainability of raw materials and manufacturing processes but also extends to the sustainability of the entire product life cycle, which requires manufacturers to act responsibly with their suppliers, implement sustainability standards for the selection of new suppliers, and maintain the relationships with the extant suppliers.

For many international organizations, it is challenging to audit their suppliers on a large scale for multiple factors, such as unavailability of information, internal change management, supplier

engagement, lack of resources for remediation, and complexity of supply chains. After studying many of the supplier sustainability audit reports of actual chemical companies, we simulated a chemical company and called it Company C.C., simulating the data to validate our model. To address the above-mentioned issues for our simulated Company C.C. we turned to a third-party platform for supplier sustainability assessment, namely the ECO system. The ECO system is a web-based tool, which allows procurement executives to access easy-to-use dynamic scorecards, and to monitor the sustainability performance of their suppliers as well as their continuous improvement actions. Despite the many benefits the ECO system has brought to its users, there have been many reports on its deficiencies. The main drawbacks of the supplier evaluation method used in the ECO system are summarized as follows:

1. Crisp numbers are used in the ECO system to represent the evaluation values, however, due to the complexity of the sustainable supplier selection problem, decision makers feel more comfortable expressing their opinions in the form of linguistic terms.
2. The assessment information, in relation to different evaluation criteria in sustainable supplier selection problems, not only comprises objective quantitative statistical data, but also contains some subjective judgement data given by decision makers with their knowledge and experience. It is common that heterogeneous types of information must be processed before making a decision. Therefore, it is more reasonable to represent each of the criteria values in a correspondingly suitable information format.
3. The simple weighted average method is used in the ECO system as the selection mechanism for sustainable suppliers, which severely reduces the accuracy of the ranking results.

In view of the above problems, this paper proposes a heterogeneous multi-criteria decision-making (MCDM) method to improve the performance of the ECO system for addressing sustainable supplier evaluation problems. For the evaluation criteria of different features, their given assessments are denoted by respective appropriate information formats, including crisp numbers, interval numbers, and triangular fuzzy numbers (TFNs). Next, a general method based on the relative closeness to the technique for order preference by similarity to ideal solution (TOPSIS) method is used to aggregate the heterogeneous assessments of alternative suppliers into interval-valued intuitionistic fuzzy numbers (IVIFNs). Considering the uncertainties involved in the sustainability performance evaluation of decision makers on alternative suppliers, the TODIM (an acronym in Portuguese for interactive multi-criteria decision-making) method is extended to the interval-valued intuitionistic fuzzy (IVIF) environment and named the IVIF-TODIM method to produce the ranking order of all alternative suppliers. The remainder of this paper is organized as follows: Section 2 provides a review of the existing literature related to this study. In Section 3, a brief introduction is presented on the basic concepts and definitions of interval numbers, TFNs, and IVIFNs. The developed heterogeneous MCDM framework is introduced in Section 4. Section 5 provides an experimental study of a sustainable supplier selection problem in a manufacturing company by using the proposed method. Finally, the concluding remarks and future research suggestions are given in Section 6.

2. Materials and Methods

In the literature, a large number of methods have been used to evaluate and select the optimal sustainable suppliers [3–5]. The main improved approaches for selecting appropriate suppliers towards green and sustainable practices can be divided into five categories, namely, qualitative, mathematical programming, mathematical analytical, artificial intelligence, and hybrid methods [4]. Yu et al. [6] proposed an intuitionistic fuzzy TOPSIS method to select the best sustainable supplier for an automotive spare parts manufacturer. Fallahpour et al. [7] devised a hybrid model which integrated fuzzy reference programming with a fuzzy TOPSIS method to find the best suppliers under uncertainty. Awasthi et al. [8] provided an integrated framework based on the fuzzy analytic hierarchy process–VlseKriterijumska Optimizacija I Kompromisno Resenje (AHP—VIKOR) approach

for sustainable global supplier selection, where sustainability risks from sub-suppliers were taken into account. By considering the criteria interrelationships, Song et al. [9] adopted the decision making trial and evaluation laboratory (DEMATEL) method and the rough numbers for handling a sustainable supplier selection problem. For solving the problem of supplier selection, Luan et al. [10] developed an artificial intelligence (AI) based model which combined the advantages of a genetic algorithm (GA) with great global convergence and ant colony optimization (ACO) with parallelism and effective feedback. Haeri and Rezaei [11] presented a grey-based supplier selection model for an uncertain environment, where the best-worst method was combined with the fuzzy grey cognitive maps to compute the criteria weights and the grey relational analysis (GRA) method was advanced to evaluate and rank green suppliers.

The sustainable supplier selection problem is becoming increasingly complex because of the ambiguous information, incomplete information, and the dilemmas of human thinking, which makes it difficult to use numerical values to address the accurate information of alternatives and decision makers [12]. A lot of modeling efforts focus on applying fuzzy concepts, such as fuzzy sets [13,14], interval-valued intuitionistic uncertain linguistic set [15], interval type-two fuzzy sets [3], and rough numbers [12] to deal with the uncertainty and fuzziness involved in the assessment information. In this paper, heterogeneous expression domains of preferences are used to assess the sustainability performance of suppliers, which is not only able to consider the uncertainty involved in the supplier evaluation process, but also can differentiate the nature of the evaluation criteria, that is either quantitative or qualitative. Quantitative criteria are those measured by numerical values which tend to be objective data and based on facts, while qualitative criteria are those measured by linguistic expressions. Motivated by the advantage of the heterogeneous information, it has been effectively used to address various types of decision-making problems, such as product ranking [16], cloud computing service evaluation [17], and supplier evaluation [18].

Among all the methods developed for the sustainable supplier selection problems, the MCDM methods are one of the most widely used methods, as the decision made in the sustainable supplier selection process naturally requires multiple goals incorporating criteria in an uncertain environment. The TODIM method is an effective MCDM method for solving decision-making problems which considers the decision makers' behavior [19]. For instance, Qin et al. [20] developed a TODIM-based method to select a renewable energy alternative, where the psychological behavior of decision makers was captured to derive a well-rounded decision. Ren et al. [21] extended the TODIM approach by considering the decision makers' attitude under risk and applied this to solve MCDM problems using Pythagorean fuzzy information. The TODIM method was also extended by Li and Cao [19] for emergency evacuations where the decision makers' psychological behavior must be considered. In this paper, the TODIM method is used to reach a more reasonable ranking result of the suppliers.

3. Preliminaries

This section presents some basic notations and definitions of interval numbers, TFNs, and interval-valued intuitionistic fuzzy sets (IVIFSs).

3.1. Interval Numbers

Interval arithmetic, which was proposed by Moore [22], is an extension of real arithmetic. In interval arithmetic, an interval number $\widehat{z}$ is expressed as an ordered pair of real numbers $\widehat{z} = [\underline{z}, \overline{z}]$, with $\underline{z} \le z \le \overline{z}$, where $\underline{z}$ and $\overline{z}$ denote the lower and upper bounds of $\widehat{z}$, respectively. It is noteworthy that $\widehat{z}$ turns into a crisp number denoted as z if $\underline{z} = \overline{z}$.

Definition 1. *For any two interval numbers $\widehat{z}_1 = \left[\underline{z}_1, \overline{z}_1\right]$ and $\widehat{z}_2 = \left[\underline{z}_2, \overline{z}_2\right]$, and $\lambda > 0$, their basic operational rules are given below [22]:*

$$\widehat{z}_1 + \widehat{z}_2 = \left[\underline{z}_1, \overline{z}_1\right] + \left[\underline{z}_2, \overline{z}_2\right] = \left[\underline{z}_1 + \overline{z}_1, \underline{z}_2 + \overline{z}_2\right] \tag{1}$$

$$\lambda \widehat{z}_1 = \lambda\left[\underline{z}_1, \bar{z}_1\right] = \left[\underline{z}_1, \bar{z}_1\right]\lambda = \left[\lambda\underline{z}_1, \lambda\bar{z}_1\right] \tag{2}$$

where λ is a non-negative real number.

Definition 2. *Let $\widehat{z}_1 = \left[\underline{z}_1, \bar{z}_1\right]$ and $\widehat{z}_2 = \left[\underline{z}_2, \bar{z}_2\right]$ be two interval numbers, then the Hamming distance between $\widehat{z}_1$ and $\widehat{z}_2$ is obtained by*

$$d_{IN} = \left(\widehat{z}_1, \widehat{z}_2\right) = \frac{1}{2}\left(\left|\underline{z}_1 - \underline{z}_2\right| + \left|\bar{z}_1 - \bar{z}_2\right|\right). \tag{3}$$

3.2. Triangular Fuzzy Sets

The fuzzy set concept, proposed by Zadeh [23], is commonly used to formulate those uncertain factors.

Definition 3. [24] *Given a fuzzy set $\widetilde{a} = (a, b, c)$, where $a < b < c$ and defined on $R = (-\infty, \infty)$, $\widetilde{a}$ is called the triangular fuzzy number (TFN), if the membership function of $\widetilde{a}$ is denoted as*

$$\mu_{\widetilde{a}}(x) = \begin{cases} \frac{(x-a)}{(b-a)}, & a \leq x \leq b, \\ \frac{(c-x)}{(c-b)}, & b \leq x \leq c, \\ 0 & otherwise, \end{cases} \tag{4}$$

where a is the least possible value, b is the main value, and c is the highest possible value.

Then, the centroid of $\widetilde{a}$ can be obtained as

$$C(\widetilde{a}) = \frac{\int_{-\infty}^{\infty} x\mu_{\widetilde{a}}(x)dx}{\int_{-\infty}^{\infty} \mu_{\widetilde{a}}(x)dx} = \frac{1}{3}(a + b + c). \tag{5}$$

It is to note that Equation (5) is often used to convert a triangular fuzzy number into a crisp number.

Definition 4. [24] *Let $\widetilde{a}_1$ and $\widetilde{a}_2$ be two TFNs, and $\lambda > 0$, the basic operational laws of two TFNs are given as follows:*

$$\widetilde{a}_1 + \widetilde{a}_2 = (a_1, b_1, c_1) + (a_2, b_2, c_2) = (a_1 + a_2, b_1 + b_2, c_1 + c_2); \tag{6}$$

$$\lambda\widetilde{a}_1 = \lambda(a_1, b_1, c_1) = (\lambda a_1, \lambda b_1, \lambda c_1). \tag{7}$$

Definition 5. *Let $\widetilde{a}_1$ and $\widetilde{a}_2$ be two TFNs, the Hamming distance between two TFNs is defined as*

$$d_{TFN}(\widetilde{a}_1, \widetilde{a}_2) = \frac{1}{3}(|a_1 - a_2| + |b_1 - b_2| + |c_1 - c_2|). \tag{8}$$

3.3. Interval-Valued Intuitionistic Fuzzy Sets

IVIFSs, originally introduced by Atanassov and Gargov [25], features a membership function and a non-membership function whose values are interval numbers rather than crisp numbers.

Definition 6. *Let X be a non-empty set of the universe and an IVIFN in X is defined as*

$$\widetilde{A} = \left\{ \left\langle x, \widetilde{\mu}_{\widetilde{A}}(x), \widetilde{V}_{\widetilde{A}}(x) \right\rangle \middle| x \in X \right\}, \tag{9}$$

where $\widetilde{\mu}_{\widetilde{A}}(x) = \left[\mu_{\widetilde{A}}^L(x), \mu_{\widetilde{A}}^U(x)\right] \subseteq [0,1]$ and $\widetilde{v}_{\widetilde{A}}(x) = \left[v_{\widetilde{A}}^L(x), v_{\widetilde{A}}^U(x)\right] \subseteq [0,1]$ are interval numbers indicating the membership degree and non-membership degree of the element $x \in X$, which satisfies $\widetilde{\mu}_{\widetilde{A}}(x) + \widetilde{v}_{\widetilde{A}}(x) \in [0,1]$ for any $x \in X$. $\pi_{\widetilde{A}}(x) = \left[\pi_{\widetilde{A}}^L(x), \pi_{\widetilde{A}}^U(x)\right]$ is the hesitation degree of element x which belongs to $\widetilde{A}$, where $\pi_{\widetilde{A}}^L(x) = 1 - \mu_{\widetilde{A}}^U(x) - v_{\widetilde{A}}^U(x)$ and $\pi_{\widetilde{A}}^U(x) = 1 - \mu_{\widetilde{A}}^L(x) - v_{\widetilde{A}}^L(x)$.

It is to note that, for every $x \in X$, if $\widetilde{\mu}_{\widetilde{A}}(x) = \mu_{\widetilde{A}}^L(x) = \mu_{\widetilde{A}}^U(x)$ and $\widetilde{v}_{\widetilde{A}}(x) = v_{\widetilde{A}}^L(x) = v_{\widetilde{A}}^U(x)$, then IVIFS $\widetilde{A}$ is degraded to an intuitionistic fuzzy set [26].

$\left(\left[\mu_{\widetilde{A}}^L(x), \mu_{\widetilde{A}}^U(x)\right], \left[v_{\widetilde{A}}^L(x), v_{\widetilde{A}}^U(x)\right]\right)$ was called an interval-valued intuitionistic fuzzy number (IVIFN) in Xu and Chen [27]. Therefore, an IVIFN can be simply denoted by $\widetilde{\alpha} = \left(\left[\mu^L, \mu^U\right], \left[v^L, v^U\right]\right)$, where $\left[\mu^L, \mu^U\right] \subseteq [0,1], \left[v^L, v^U\right] \subseteq [0,1], \mu^U + v^U \leq 1$.

Definition 7. *Let* $\widetilde{\alpha}_1 = \left(\left[\mu_1^L, \mu_1^U\right], \left[v_1^L, v_1^U\right]\right)$ *and* $\widetilde{\alpha}_2 = \left(\left[\mu_2^L, \mu_2^U\right], \left[v_2^L, v_2^U\right]\right)$ *be two IVIFNs, and* $\lambda > 0$, *the basic operational laws of IVIFNs are defined as follows* [28]:

$$\widetilde{\alpha}_1 + \widetilde{\alpha}_2 = \left(\left[\mu_1^L + \mu_2^L - \mu_1^L\mu_2^L, \mu_1^U + \mu_2^U - \mu_1^U\mu_2^U\right], \left[v_1^L v_2^L, v_1^U v_2^U\right]\right); \tag{10}$$

$$\widetilde{\alpha}_1 \widetilde{\alpha}_2 = \left(\left[\mu_1^L\mu_2^L, \mu_1^U\mu_2^U\right], \left[v_1^L + v_2^L - v_1^L v_2^L, v_1^U + v_2^U - v_1^U v_2^U\right]\right); \tag{11}$$

$$\lambda\widetilde{\alpha}_1 = \left(\left[1 - \left(1 - \mu_1^L\right)^\lambda, 1 - \left(1 - \mu_1^U\right)^\lambda\right], \left[\left(v_1^L\right)^\lambda, \left(v_1^U\right)^\lambda\right]\right); \tag{12}$$

$$\widetilde{\alpha}_1^\lambda = \left(\left[\left(\mu_1^L\right)^\lambda, \left(\mu_1^U\right)^\lambda\right], \left[1 - \left(1 - v_1^L\right)^\lambda, 1 - \left(1 - v_1^U\right)^\lambda\right]\right); \tag{13}$$

Definition 8. [27] *Let* $\widetilde{\alpha} = \left(\left[\mu^L, \mu^U\right], \left[v^L, v^U\right]\right)$ *be an IVIFN, the score function and the accuracy function of* $\widetilde{\alpha}$ *can be defined by*

$$S(\widetilde{\alpha}) = \frac{1}{2}\left(\mu^L + \mu^U - v^L - v^U\right), \tag{14}$$

$$H(\widetilde{\alpha}) = \frac{1}{2}\left(\mu^L + \mu^U + v^L + v^U\right),. \tag{15}$$

where $S(\widetilde{\alpha}) \in [-1,1]$ *and* $H(\widetilde{\alpha}) \in [0,1]$.

Definition 9. *Let* $\widetilde{\alpha}_1 = \left(\left[\mu_1^L, \mu_1^U\right], \left[v_1^L, v_1^U\right]\right)$ *and* $\widetilde{\alpha}_2 = \left(\left[\mu_2^L, \mu_2^U\right], \left[v_2^L, v_2^U\right]\right)$ *be two IVIFNs, the comparison laws of two IVIFNs are defined as follows* [28]:

(1) *If* $S(\widetilde{\alpha}_1) < S(\widetilde{\alpha}_2)$, *then* $\widetilde{\alpha}_1 < \widetilde{\alpha}_2$.
(2) *If* $S(\widetilde{\alpha}_1) = S(\widetilde{\alpha}_2)$, *then*

(a) *If* $H(\widetilde{\alpha}_1) < H(\widetilde{\alpha}_2)$, *then* $\widetilde{\alpha}_1 < \widetilde{\alpha}_2$.
(b) *If* $H(\widetilde{\alpha}_1) = H(\widetilde{\alpha}_2)$, *then* $\widetilde{\alpha}_1 = \widetilde{\alpha}_2$.

Definition 10. [27] *Given a set of IVIFNs* $\widetilde{\alpha}_j = \left(\left[\mu_j^L, \mu_j^U\right], \left[v_j^L, v_j^U\right]\right)(j = 1, 2, \ldots, n)$, *with the associated weight vector* $w = (w_1, w_2, \ldots, w_n)^T$ *satisfying* $w_j \in [0,1]$ *and* $\sum_{j=1}^{n} w_j = 1$, *the interval-valued intuitionistic fuzzy weighted averaging (IVIFWA) is defined as*
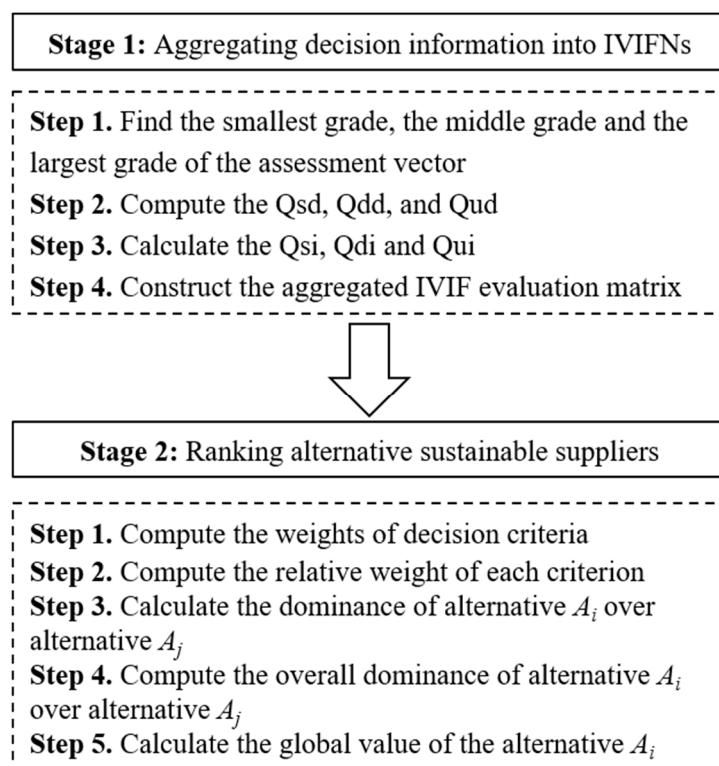
$$\begin{aligned}
IVIFWA(\widetilde{\alpha}_1, \widetilde{\alpha}_2, \ldots, \widetilde{\alpha}_n) &= \sum_{j=1}^{n} w_j\widetilde{\alpha}_j \\
&= \left(\left[1 - \prod_{j=1}^{n}\left(1 - \mu_j^L\right)^{w_j}, 1 - \prod_{j=1}^{n}\left(1 - \mu_j^U\right)^{w_j}\right], \left[\prod_{j=1}^{n}\left(v_j^L\right)^{w_j}, \prod_{j=1}^{n}\left(v_j^U\right)^{w_j}\right]\right).
\end{aligned} \tag{16}$$

Definition 11. [29] *Let $\widetilde{\alpha}_1 = \left(\left[\mu_1^L, \mu_1^U \right], \left[v_1^L, v_1^U \right] \right)$ and $\widetilde{\alpha}_2 = \left(\left[\mu_2^L, \mu_2^U \right], \left[v_2^L, v_2^U \right] \right)$ be two IVIFNs, the Hamming distance between two IVIFNs is defined as follows:*

$$d_{IVIFN}(\widetilde{\alpha}_1, \widetilde{\alpha}_2) = \frac{1}{4} \left(\left| \mu_1^L - \mu_2^L \right| + \left| \mu_1^U - \mu_2^U \right| + \left| v_1^L - v_2^L \right| + \left| v_1^U - v_2^U \right| \right). \tag{17}$$

4. The Proposed Sustainable Supplier Selection

In this section, we propose a heterogeneous MCDM method to select the most favorable sustainable supplier with the evaluation information taking different formats. In the proposed method, the evaluation information involves crisp values, interval numbers, and TFNs. The proposed method consists of two stages and its flowchart is displayed in Figure 1. First, a TOPSIS-based method is used to aggregate the heterogeneous evaluation information given by decision makers on each supplier with respect to different criteria into IVIFNs. Secondly, the IVIF-TODIM method is introduced for ranking the alternative sustainable suppliers.

Stage 1: Aggregating decision information into IVIFNs

Step 1. Find the smallest grade, the middle grade and the largest grade of the assessment vector
Step 2. Compute the Qsd, Qdd, and Qud
Step 3. Calculate the Qsi, Qdi and Qui
Step 4. Construct the aggregated IVIF evaluation matrix

Stage 2: Ranking alternative sustainable suppliers

Step 1. Compute the weights of decision criteria
Step 2. Compute the relative weight of each criterion
Step 3. Calculate the dominance of alternative A_i over alternative A_j
Step 4. Compute the overall dominance of alternative A_i over alternative A_j
Step 5. Calculate the global value of the alternative A_i

Figure 1. The flowchart of the proposed method.

Suppose a sustainable supplier selection problem with three forms of assessment values. The set of alternatives is represented by $A_i (i = 1, 2, \ldots, m)$. The m alternatives are evaluated in relation to n decision criteria $C_j (j = 1, 2, \ldots, n)$ by l decision makers $DM_k (k = 1, 2, \ldots, l)$. When evaluating the alternative suppliers under different risk factors and the relative importance of decision criteria, different types of information, including crisp values, interval numbers, and TFNs may be used. Assume that $G_k = \left(g_{ij}^k \right)_{m \times n}$ is the evaluation matrix provided by the kth decision maker, where g_{ij}^k indicates heterogeneous assessment value given by DM_k over A_i in relation to C_j. According to the framework illustrated in Figure 1, the detailed description of the proposed method is outlined below.

4.1. Aggregating Decision Information into IVIFNs

For processing heterogeneous information, Wan et al. [30] developed a general method using the concept of relative closeness of the TOPSIS method. The main advantage of this aggregating method is that it can aggregate different types of decision information into IVIFNs, including crisp values, interval numbers, and TFNs. The steps of the aggregating method are the following:

Step 1 Find the smallest grade, the middle grade, and the largest grade of the assessment vector.

For simplicity, the j_{th} column vector in $G_k = \left(g_{ij}^k \right)_{m \times n}$ is denoted as $C_{ij} = \left(g_{ij}^1, g_{ij}^2, \ldots, g_{ij}^l \right)$, indicating the assessment vector of alternative A_m on criterion C_j provided by all decision makers DM_k. The largest grade $C_j^{\max}$, the middle grade C_j^{mid}, and the smallest grade $C_j^{\min}$ of the assessment vector, respectively, mean the largest grade and the smallest grade in the rating system (e.g., in the 10-point numerical scale for the ratings of crisp numbers, $C_j^{\max} = 10$, $C_j^{\mathrm{mid}} = 5$ and $C_j^{\min} = 0$).

Step 2 Compute the quasi-satisfactory degree, quasi-uncertain degree, and quasi-uncertain degree.

Considering the complexity and fuzziness involved in different information formats, quasi-satisfactory degree (Qsd), quasi-dissatisfactory degree (Qdd) and quasi-uncertain degree (Qud) of each element are introduced to measure the decision preference of the decision makers. If the distance between g_{ij}^k and $C_j^{\min}$ is greater than the distance between g_{ij}^k and $C_j^{\max}$, then the decision makers prefer satisfaction. If the distance between g_{ij}^k and $C_j^{\min}$ is less than the distance between g_{ij}^k and $C_j^{\max}$, then the decision makers prefer dissatisfaction. If the distance between g_{ij}^k and $C_j^{\min}$ is equal to the distance between g_{ij}^k and $C_j^{\max}$, then the decision makers maintain neutrality.

The Qsd, Qdd, and Qud of each assessment value g_{ij}^k, denoted as ξ_{ij}^k, ζ_{ij}^k, and η_{ij}^k, respectively, can be derived by

$$\xi_{ij}^k = \frac{d\left(g_{ij}^k, C_j^{\min} \right)}{d\left(g_{ij}^k, C_j^{\max} \right) + d\left(g_{ij}^k, C_j^{\min} \right)}, \tag{18}$$

$$\zeta_{ij}^k = 1 - \xi_{ij}^k, \tag{19}$$

$$\eta_{ij}^k = \begin{cases} \dfrac{d\left(g_{ij}^k, C_j^{\max} \right)}{d\left(g_{ij}^k, C_j^{\max} \right) + d\left(g_{ij}^k, C_j^{\mathrm{mid}} \right)}, & if\ d\left(g_{ij}^k, C_j^{\max} \right) < d\left(g_{ij}^k, C_j^{\min} \right), \\[2ex] \dfrac{d\left(g_{ij}^k, C_j^{\min} \right)}{d\left(g_{ij}^k, C_j^{\min} \right) + d\left(g_{ij}^k, C_j^{\mathrm{mid}} \right)}, & if\ d\left(g_{ij}^k, C_j^{\max} \right) > d\left(g_{ij}^k, C_j^{\min} \right), \\[2ex] 1, & if\ d\left(g_{ij}^k, C_j^{\max} \right) = d\left(g_{ij}^k, C_j^{\min} \right), \end{cases} \tag{20}$$

where $d\left(g_{ij}^k, C_j^{\max} \right)$ is the distance between g_{ij}^k and $C_j^{\max}$, $d\left(g_{ij}^k, C_j^{\min} \right)$ is the distance between g_{ij}^k and $C_j^{\min}$, and $d\left(g_{ij}^k, C_j^{\mathrm{mid}} \right)$ is the distance between g_{ij}^k and C_j^{mid}.

Step 3 Calculate the Qsi, Qdi, and Qui.

Since the membership degree and non-membership degree of an IVIFN are intervals rather than crisp numbers, it is more reasonable to use the ranges of Qsd, Qdd, and Qud, which are named as quasi-satisfactory interval (Qsi), quasi-dissatisfactory interval (Qdi), and quasi-uncertain interval (Qui), respectively, as the measurement of the decision makers' preference. The Qsi, Qdi, and Qui denoted as $\widetilde{\xi}_{ij}$, $\widetilde{\zeta}_{ij}$, and $\widetilde{\eta}_{ij}$, respectively, are computed via

$$\widetilde{\xi}_{ij} = \left[\xi_{ij}^p, \xi_{ij}^q \right] = \left[\max\left(l\left(\xi_{ij} \right) - d\left(\xi_{ij} \right), 0 \right), l\left(\xi_{ij} \right) + d\left(\xi_{ij} \right) \right], \tag{21}$$

$$\widetilde{\zeta}_{ij} = \left[\zeta_{ij}^p, \zeta_{ij}^q \right] = \left[\max\left(l\left(\zeta_{ij} \right) - d\left(\zeta_{ij} \right), 0 \right), l\left(\zeta_{ij} \right) + d\left(\zeta_{ij} \right) \right], \tag{22}$$

$$\widetilde{\eta}_{ij} = \left[\eta_{ij}^p, \eta_{ij}^q\right] = \left[\max\left(l\left(\eta_{ij}\right) - d\left(\eta_{ij}\right), 0\right), l\left(\eta_{ij}\right) + d\left(\eta_{ij}\right)\right],\tag{23}$$

for $i = 1, 2 \ldots, m$ and $j = 1, 2, \ldots, n$. $l\left(\xi_{ij}\right) = \frac{1}{l}\sum_{k=1}^{l}\xi_{ij}^k$, $l\left(\zeta_{ij}\right) = 1 - l\left(\xi_{ij}\right)$, $l\left(\eta_{ij}\right) = \frac{1}{l}\sum_{k=1}^{l}\eta_{ij}^k$, $d\left(\xi_{ij}\right) = \sqrt{\frac{1}{l-1}\sum_{k=1}^{l}\left(\xi_{ij}^k - l\left(\xi_{ij}\right)\right)^2}$, $d\left(\zeta_{ij}\right) = \sqrt{\frac{1}{l-1}\sum_{k=1}^{l}\left(\zeta_{ij}^k - l\left(\zeta_{ij}\right)\right)^2}$ and $d\left(\eta_{ij}\right) = \sqrt{\frac{1}{l-1}\sum_{k=1}^{l}\left(\eta_{ij}^k - l\left(\eta_{ij}\right)\right)^2}$ are the mean values and standard deviation of ξ_{ij}^k, ζ_{ij}^k, and η_{ij}^k, respectively. Here, an ordered pair $\left(\left[\xi_{ij}^p, \xi_{ij}^q\right], \left[\zeta_{ij}^p, \zeta_{ij}^q\right]\right)$ is called a quasi-IVIFN.

Step 4 Construct the aggregated IVIF evaluation matrix.

The algorithm for transforming the quasi-IVIFN into an IVIFN denoted as $\widetilde{\alpha}_{ij}$ is given as

$$\begin{aligned}
\widetilde{\alpha}_{ij} &= \left(\left[\mu_{ij}^p, \mu_{ij}^q\right], \left[v_{ij}^p, v_{ij}^q\right]\right),\\
\mu_{ij}^p &= \xi_{ij}^p/\psi_{ij}, \mu_{ij}^q = \xi_{ij}^q/\psi_{ij}, v_{ij}^p = \zeta_{ij}^p/\psi_{ij}, v_{ij}^q = \zeta_{ij}^q/\psi_{ij},
\end{aligned}\tag{24}$$

where $\psi_{ij} = \xi_{ij}^p + \xi_{ij}^q + \zeta_{ij}^p + \zeta_{ij}^q + \frac{1}{2}\left(\eta_{ij}^p + \eta_{ij}^q\right)$. By using Equation (24) all the elements in the evaluation vector $C_{ij} = \left(g_{ij}^1, g_{ij}^2, \ldots, g_{ij}^l\right)$ can be transformed into IVIFNs and the collective IVIF evaluation matrix $\widetilde{G} = \left(\widetilde{g}_{ij}\right)_{m\times n}$, where $\widetilde{g}_{ij}^k$ is the collective IVIF assessment value over A_i in relation to C_j.

4.2. Ranking Alternative Sustainable Suppliers

The TODIM method was proposed by Gomes and Lima [31], which is a discrete multi-criteria method based on prospect theory. The TODIM method is a valuable technique which can take into account the decision makers' psychological behavior when dealing with the uncertainty involved in the MCDM problems. In the second stage of the proposed sustainable supplier evaluation method, the TODIM method is extended to the IVIF circumstance to derive the ranking order of the alternative sustainable suppliers. The steps of the IVIF-TODIM method are listed as follows:

Step 1 Compute the weights of decision criteria.

The relative importance of each criterion is evaluated by decision makers using TFNs. Let $W^k = \left(\widetilde{w}_j^k\right)_{1\times n}$ be the triangular fuzzy weight vector of decision criteria C_j, where $\widetilde{w}_j^k$ is a TFN provided by DM_k to reflect the relative importance of each criterion in the ranking of alternatives. After obtaining the triangular fuzzy weight vector of decision criteria, the weight of each decision criterion can be determined by

$$\overline{w}_j = \frac{\sum_{k=1}^{l}\omega_k C\left(\widetilde{w}_j\right)}{\sum_{j=1}^{n}\sum_{k=1}^{l}C\left(\omega_k\widetilde{w}_j\right)}, j = 1, 2, \ldots, n,\tag{25}$$

where $C\left(\widetilde{w}_j\right)$ is the centroid of $\widetilde{w}_j$ which is computed via Equation (5) and ω_k is the relative importance of the decision makers.

Step 2 Compute the relative weight of each criterion.

The weight of the reference criterion c_r can be determined via

$$\overline{w}_r = \max\left\{\overline{w}_j \middle| j = 1, 2, \ldots, n\right\}.\tag{26}$$

Then the relative weight of alternative c_j to the reference criterion c_r can be computed by

$$\overline{w}_{jr} = \frac{\overline{w}_j}{\overline{w}_r}.\tag{27}$$

Step 3 Calculate the dominance of alternative A_i over alternative A_j.

The measurement of the dominance of each alternative A_i over each alternative A_f under the criterion c_j can be given by

$$
\phi_j\left(A_i, A_f\right) =
\begin{cases}
\sqrt{\dfrac{\overline{w}_{jr}}{\sum\limits_{j=1}^{n} \overline{w}_{jr}} d\left(\widetilde{g}_{ij}, \widetilde{g}_{fj}\right)} & , \ if \ \widetilde{g}_{ij} > \widetilde{g}_{fj}, \\[6pt]
0 & , \ if \ \widetilde{g}_{ij} = \widetilde{g}_{fj}, \\[6pt]
\dfrac{-1}{\sigma} \sqrt{\dfrac{\sum\limits_{j=1}^{n} \overline{w}_{jr}}{\overline{w}_{jr}} d\left(\widetilde{g}_{ij}, \widetilde{g}_{fj}\right)} & , \ if \ \widetilde{g}_{ij} < \widetilde{g}_{fj},
\end{cases}
\tag{28}
$$

where the parameter σ denotes the attenuation factor of losses, and $d\left(\widetilde{g}_{ij}, \widetilde{g}_{fj}\right)$ indicates the distance between the two elements $\widetilde{g}_{ij}$ and $\widetilde{g}_{fj}$ in the collective IVIF evaluation matrix $\widetilde{G} = \left(\widetilde{g}_{ij}\right)_{m \times n}$.

Step 4 Compute the overall dominance of alternative A_i over alternative A_j.

By summing up the dominance of alternative A_i over alternative A_j under each decision criterion, the overall dominance of alternative A_i over alternative A_j can be achieved by

$$
\Phi\left(A_i, A_f\right) = \sum_{j=1}^{n} \phi_j(A_i, A_h).
\tag{29}
$$

Step 5 Calculate the global value of the alternative A_i.

Finally, the global value of each alternative A_i, which is used as the indicator for the suppliers' sustainability performance, can be derived by

$$
\vartheta_i = \frac{\sum\limits_{f=1}^{m} \Phi\left(A_i, A_f\right) - \min\limits_{i}\left(\sum\limits_{f=1}^{m} \Phi\left(A_i, A_f\right)\right)}{\max\limits_{i}\left(\sum\limits_{f=1}^{m} \Phi\left(A_i, A_f\right)\right) - \min\limits_{i}\left(\sum\limits_{f=1}^{m} \Phi\left(A_i, A_f\right)\right)}, \quad i = 1, 2, \ldots, m.
\tag{30}
$$

The best alternatives are those with bigger value ϑ_i. Thus, the ranking for all the alternative suppliers can be gained corresponding to the descending order of their global values $\vartheta_i (i = 1, 2, \ldots, m)$.

5. Case Study

5.1. Implementation

Our simulated Company C.C., is a leading manufacturer of high-tech premium polymers, in which sustainability is regarded as one of the most important driving forces behind the continuous development of its products, processes, and facilities. In order to safeguard its global competitiveness and the supply of materials and services, it operates responsibly in collaboration with its suppliers, aiming to mitigate risks and create stable, long-term business relationships with its partners. It follows a four-step process, including supplier awareness, supplier nomination, supplier sustainability performance evaluation, and supplier development, in order to improve sustainability practices within a supply chain. When choosing new suppliers or continuing its relationships with existing ones, the company applies not only economic standards, but also environmental, social, and corporate governance standards. These standards are divided into four themes which include environment (EVN), labor practices (LAB), fair business practices (FBP), and sustainable procurement (SUP), and these standards are used as the criteria for evaluating the sustainability performance of its selected suppliers.

Suppose that after pre-assessment, Company C.C. nominates a list of potential suppliers $(A_i, i = 1, 2, \ldots, 5)$ for further evaluation and selection. These nominated suppliers are evaluated with respect to four evaluation criteria $\left(C_j, j = 1, 2, 3, 4\right)$, which are EVN, LAB, FBP, and SUP. In order to

choose the best supplier, a committee of three decision makers, $(\text{DM}_k, k = 1, 2, 3)$ is formed. These experts are from different departments including a full-time auditor, a sourcing manager, and head of the sustainable development department. Note that the proposed approach is applicable to any number of team members and the three experts selected in this case are for demonstration purposes only. The weights for the three decision makers are given as $\lambda_1 = 0.3$, $\lambda_2 = 0.3$ and $\lambda_3 = 0.4$. Specifically, the crisp values and the interval numbers with the same zero to 10 qualitative scale are used to express the assessments provided by decision makers on each supplier with respect to the evaluation criteria EVN and LAB, respectively. While, the TFNs (Table 1) are applied to express the risk assessments provide by decision makers on each supplier with respect to both of the evaluation criteria FBP and SUP. The computational procedures conducted in this case are explained according to each step of the proposed sustainable supplier selection method.

Table 1. Linguistic terms for triangular fuzzy numbers (TFNs).

Linguistic Terms of Suppliers	Linguistic Terms of Criteria	TFNs
Very poor	Very low	(0,0,1)
Poor	Low	(0,1,3)
Middle poor	Middle low	(1,3,5)
Middle	Middle	(3,5,7)
Middle good	Middle high	(5,7,9)
Good	High	(7,9,10)
Very good	Very high	(9,10,10)

The assessments of the five suppliers given by the three decision makers are provided in Table 2.

Table 2. Evaluation matrix of five suppliers.

DMs	Suppliers	C_1	C_2	C_3	C_4
	A_1	9	[7,8]	(5,7,9)	(7,9,10)
	A_2	8	[7,7]	(1,3,5)	(9,10,10)
DM$_1$	A_3	8	[6,7]	(5,7,9)	(0,1,3)
	A_4	9	[7,8]	(3,5,7)	(3,5,7)
	A_5	6	[8,8]	(3,5,7)	(9,10,10)
	A_1	8	[6,6]	(5,7,9)	(1,3,5)
	A_2	7	[7,8]	(5,7,9)	(3,5,7)
DM$_2$	A_3	9	[7,8]	(7,9,10)	(1,3,5)
	A_4	8	[7,7]	(5,7,9)	(3,5,7)
	A_5	8	[6,7]	(5,7,9)	(5,7,9)
	A_1	7	[7,8]	(7,9,10)	(3,5,7)
	A_2	8	[6,7]	(5,7,9)	(5,7,9)
DM$_3$	A_3	8	[7,8]	(5,7,9)	(1,3,5)
	A_4	7	[7,7]	(3,5,7)	(3,5,7)
	A_5	8	[6,6]	(1,3,5)	(3,5,7)

Stage 1: Aggregating decision information into IVIFNs.

Step 1 Since the assessment values are given according to the ten-mark system, the smallest grade, the middle grade, and the largest grade of the assessment vector is determined as follows:

If the assessment value is given as the crisp number, then $C_j^{\min} = 0$, $C_j^{\text{mid}} = 5$ and $C_j^{\max} = 10$; if the assessment value is given as the interval numbers, then $C_j^{\min} = [0, 0]$, $C_j^{\text{mid}} = [5, 5]$ and $C_j^{\max} = [10, 10]$; if the assessment value is given as the TFNs, then $C_j^{\min} = [0, 0, 0]$, $C_j^{\text{mid}} = [5, 5, 5]$ and $C_j^{\max} = [10, 10, 10]$.

Step 2 By using Equations (18) to (20), the Qsd, Qdd, and Qud of each assessment value is derived and shown in Table 3.

Table 3. Quasi-satisfactory degree (Qsd), quasi-dissatisfactory degree (Qdd), and quasi-uncertain degree (Qud) of each assessment value.

DMs	Suppliers	C_1	C_2	C_3	C_4
	A_1	0.90,0.10,0.20	0.75,0.25,0.50	0.70,0.30,0.60	0.87,0.13,0.27
	A_2	0.80,0.20,0.40	0.70,0.30,0.60	0.30,0.70,0.60	0.97,0.03,0.07
DM_1	A_3	0.80,0.20,0.40	0.65,0.35,0.70	0.70,0.30,0.60	0.13,0.87,0.27
	A_4	0.90,0.10,0.20	0.75,0.25,0.50	0.50,0.50,1.00	0.50,0.50,1.00
	A_5	0.60,0.40,0.80	0.80,0.20,0.40	0.50,0.50,1.00	0.97,0.03,0.07
	A_1	0.80,0.20,0.40	0.60,0.40,0.80	0.70,0.30,0.60	0.30,0.70,0.60
	A_2	0.70,0.30,0.60	0.75,0.25,0.50	0.70,0.30,0.60	0.50,0.50,1.00
DM_2	A_3	0.90,0.10,0.20	0.75,0.25,0.50	0.87,0.13,0.27	0.30,0.70,0.60
	A_4	0.80,0.20,0.40	0.70,0.30,0.60	0.70,0.30,0.60	0.50,0.50,1.00
	A_5	0.80,0.20,0.40	0.65,0.35,0.70	0.70,0.30,0.60	0.70,0.30,0.60
	A_1	0.70,0.30,0.60	0.75,0.25,0.50	0.80,0.20,0.27	0.50,0.50,1.00
	A_2	0.80,0.20,0.40	0.65,0.35,0.70	0.70,0.30,0.60	0.70,0.30,0.60
DM_3	A_3	0.80,0.20,0.40	0.75,0.25,0.50	0.70,0.30,0.60	0.30,0.70,0.60
	A_4	0.70,0.30,0.60	0.70,0.30,0.60	0.50,0.50,1.00	0.50,0.50,1.00
	A_5	0.80,0.20,0.40	0.60,0.40,0.80	0.30,0.70,0.60	0.50,0.50,1.00

Step 3 Using Equations (21) to (23), the Qsi, Qdi, and Qui can be computed and presented in Table 4.

Step 4 By Equation (24), the induced IVIFNs of assessment vectors can be obtained and displayed in Table 4.

Table 4. Qsi, Qdi, Qui, and the aggregated interval-valued intuitionistic fuzzy numbers (IVIFNs).

Suppliers	Criteria	$\tilde{\xi}_{ij}$	$\tilde{\zeta}_{ij}$	$\tilde{\eta}_{ij}$	IVIFNs
	C_1	[0.700, 0.900]	[0.100, 0.300]	[0.200, 0.600]	([0.292, 0.375], [0.042, 0.125])
A_1	C_2	[0.613, 0.787]	[0.213, 0.387]	[0.427, 0.773]	([0.236, 0.303], [0.082, 0.149])
	C_3	[0.659, 0.852]	[0.148, 0.341]	[0.296, 0.681]	([0.265, 0.342], [0.060, 0.137])
	C_4	[0.268, 0.843]	[0.157, 0.732]	[0.255, 0.989]	([0.102, 0.321], [0.060, 0.321])
	C_1	[0.709, 0.824]	[0.176, 0.291]	[0.351, 0.582]	([0.287, 0.334], [0.071, 0.118])
A_2	C_2	[0.650, 0.750]	[0.250, 0.350]	[0.500, 0.700]	([0.250, 0.288], [0.096, 0.135])
	C_3	[0.336, 0.798]	[0.202, 0.664]	[0.600, 0.600]	([0.135, 0.320], [0.081, 0.267])
	C_4	[0.488, 0.956]	[0.044, 0.512]	[0.087, 1.024]	([0.186, 0.365], [0.017, 0.365])
	C_1	[0.776, 0.891]	[0.109, 0.224]	[0.218, 0.449]	([0.332, 0.382], [0.047, 0.096])
A_3	C_2	[0.659, 0.774]	[0.226, 0.341]	[0.451, 0.682]	([0.257, 0.298], [0.087, 0.131])
	C_3	[0.659, 0.852]	[0.148, 0.341]	[0.296, 0.681]	([0.265, 0.342], [0.060, 0.137])
	C_4	[0.148, 0.341]	[0.659, 0.852]	[0.296, 0.681]	([0.057, 0.130], [0.251, 0.130])
	C_1	[0.700, 0.900]	[0.100, 0.300]	[0.200, 0.600]	([0.292, 0.375], [0.042, 0.125])
A_4	C_2	[0.688, 0.746]	[0.254, 0.312]	[0.509, 0.624]	([0.268, 0.287], [0.098, 0.120])
	C_3	[0.451, 0.682]	[0.318, 0.549]	[0.636, 1.098]	([0.181, 0.274], [0.128, 0.221])
	C_4	[0.500, 0.500]	[0.500, 0.500]	[1.000, 1.000]	([0.191, 0.191], [0.191, 0.191])
	C_1	[0.618, 0.849]	[0.151, 0.382]	[0.302, 0.764]	([0.244, 0.335], [0.060, 0.151])
A_5	C_2	[0.579, 0.787]	[0.213, 0.421]	[0.425, 0.841]	([0.220, 0.303], [0.082, 0.162])
	C_3	[0.300, 0.700]	[0.300, 0.700]	[0.502, 0.964]	([0.121, 0.281], [0.121, 0.281])
	C_4	[0.488, 0.956]	[0.044, 0.512]	[0.087, 1.024]	([0.186, 0.365], [0.017, 0.365])

Stage 2: Ranking alternative sustainable suppliers.

Step 1 The evaluation vector of the decision criteria is shown in Table 5. By Equation (25), the weights of the four decision criteria are derived as $\overline{w}_1 = 0.293$, $\overline{w}_2 = 0.357$, $\overline{w}_3 = 0.184$ and $\overline{w}_4 = 0.166$.

Table 5. The evaluation vector of the decision criteria.

DMs	Criteria			
	C_1	C_2	C_3	C_4
DM_1	(7,9,10)	(5,7,9)	(3,5,7)	(1,3,5)
DM_2	(5,7,9)	(7,9,10)	(3,5,7)	(1,3,5)
DM_3	(3,5,7)	(7,9,10)	(1,3,5)	(3,5,7)

Step 2 By Equations (26) and (27), the relative weight of each criterion is computed as $\overline{w}_{1r} = 0.821$, $\overline{w}_{2r} = 1.000$, $\overline{w}_{3r} = 0.515$ and $\overline{w}_{4r} = 0.465$.

Step 3 The parameter σ is taken as 1. By Equation (28), the dominance of alternative A_i over alternative A_j under each criterion is derived and presented below:

$$
\phi_1 = \begin{pmatrix}
 & A_1 & A_2 & A_3 & A_4 & A_5 \\
A_1 & 0 & 0.077 & -0.264 & 0 & 0.098 \\
A_2 & -0.264 & 0 & -0.344 & -0.264 & 0.081 \\
A_3 & 0.077 & 0.101 & 0 & 0 & 0.122 \\
A_4 & 0 & 0.077 & -0.264 & 0 & 0.098 \\
A_5 & -0.335 & -0.275 & -0.416 & -0.335 & 0
\end{pmatrix}
\tag{31}
$$

$$
\phi_2 = \begin{pmatrix}
 & A_1 & A_2 & A_3 & A_4 & A_5 \\
A_1 & 0 & 0 & -0.183 & -0.254 & 0.051 \\
A_2 & 0 & 0 & -0.142 & -0.159 & 0.088 \\
A_3 & 0.065 & 0.051 & 0 & 0 & 0.083 \\
A_4 & 0.091 & 0.057 & 0 & 0 & 0.104 \\
A_5 & -0.144 & -0.254 & -0.233 & -0.292 & 0
\end{pmatrix}
\tag{32}
$$

$$
\phi_3 = \begin{pmatrix}
 & A_1 & A_2 & A_3 & A_4 & A_5 \\
A_1 & 0 & 0.118 & 0 & 0.118 & 0.137 \\
A_2 & -0.642 & 0 & -0.642 & 0 & 0.070 \\
A_3 & 0 & 0.118 & 0 & 0.118 & 0.137 \\
A_4 & -0.642 & 0 & -0.642 & 0 & 0.079 \\
A_5 & -0.747 & -0.382 & -0.137 & -0.079 & 0
\end{pmatrix}
\tag{33}
$$

$$
\phi_4 = \begin{pmatrix}
 & A_1 & A_2 & A_3 & A_4 & A_5 \\
A_1 & 0 & -0.567 & 0.160 & 0.141 & -0.567 \\
A_2 & 0.094 & 0 & 0.186 & 0.148 & 0 \\
A_3 & -0.967 & -1.121 & 0 & -0.690 & -1.121 \\
A_4 & -0.851 & -0.891 & 0.115 & 0 & -0.891 \\
A_5 & 0.094 & 0 & 0.186 & 0.148 & 0
\end{pmatrix}
\tag{34}
$$

Step 4 By Equation (29), the overall dominance of alternative A_i over alternative A_j is obtained and displayed as follows:

$$
\Phi = \begin{pmatrix}
 & A_1 & A_2 & A_3 & A_4 & A_5 \\
A_1 & 0 & -0.372 & -0.286 & 0.005 & -0.280 \\
A_2 & -0.812 & 0 & -0.943 & -0.275 & 0.238 \\
A_3 & -0.824 & -0.851 & 0 & -0.495 & -0.778 \\
A_4 & -1.402 & -0.757 & -0.791 & 0 & -0.609 \\
A_5 & -1.132 & -0.902 & -0.600 & -0.559 & 0
\end{pmatrix}
\tag{35}
$$

Step 5 Finally, by using Equation (30), the global value of each alternative A_i is derived as $\vartheta_1 = 1$, $\vartheta_2 = 0.673$, $\vartheta_3 = 0.233$, $\vartheta_4 = 0$, $\vartheta_5 = 0.139$. Therefore, A_1 is the optimal permutation of the alternative

sustainable suppliers and the optimal ranking order of the suppliers is $A_1 > A_2 > A_3 > A_5 > A_4$. Thus, A_1 is selected as the most sustainable supplier for the simulated Company C.C.

5.2. Comparative Analysis

To further demonstrate the efficiency of the proposed sustainable supplier selection method, a comparative study was performed with several existing methods to solve the same supplier evaluation problem. As the proposed approach is designed to overcome the shortcomings of the simple weighted average algorithm applied in the ECO system, the weighted average method was selected for the comparison [32]. In addition, the TOPSIS method is among the most widely used MCDM methods for solving supplier section problems. Therefore, we also compare the proposed method with the fuzzy TOPSIS method [4] to show its merits. The ranking orders of the five alternative suppliers produced by these three methods are shown in Table 6.

Table 6. Ranking comparisons.

Suppliers	Methods		
	Weighted Average	Fuzzy TOPSIS	Proposed Method
A_1	1	1	1
A_2	2	3	2
A_3	2	2	3
A_4	4	5	5
A_5	4	4	4

As depicted in Table 6, A_1 is the optimal sustainable supplier and A_4 is the least favorable supplier by the proposed approach and the two comparative approaches, which shows the validity of the proposed model. In addition, there are some differences between the ranking orders determined by the proposed method and the two comparative methods. First, the differences between the proposed method and the weighted average method can be seen in the alternative suppliers A_2, A_3, A_4, and A_5. These differences are mainly due to the deficiencies in the simple weighted average method. As can be seen in Table 6, the alternatives, A_2 and A_3, are given the same rank by the weighted average method. However, the sustainability performance of the two suppliers is different. In contrast, the proposed method can distinguish the sustainability performance of these two suppliers by ranking A_2 before A_3. The same case can be seen in the suppliers A_4 and A_5, which also have the same rank when using the weighted method. Whereas by the proposed method, A_5 is given a higher rank than A_4.

Secondly, apart from A_2 and A_3, the ranking order for the other alternatives acquired by the proposed method is the same as those of the fuzzy TOPSIS method. The fuzzy TOPSIS method ranked A_3 before A_2. However, the results determined by the proposed method ranked A_2 higher than A_3. The inconsistency in the ranking results can be explained by the following reasons: (1) Intuitionistic fuzzy numbers are used by the fuzzy TOPSIS method to evaluate the sustainability performance of the suppliers, while the heterogeneous information is adopted in the proposed method and then aggregated into IVIFN. With the membership function and non-membership function degrees assigned in the form of intervals, the proposed method has better agility for expressing the uncertainty and ambiguity of decision makers' assessment information as it can be used to describe the characteristics of affirmation, negation, and hesitation simultaneously. (2) The ranking procedures of the fuzzy TOPSIS method are based on the assumption that the decision makers are completely rational. In contrast, based on the TODIM method, the proposed heterogeneous MCDM method has bounded rationality and takes the psychological characteristics of the team members into account, and therefore is able to derive a ranking result that is closer to the real situation.

6. Conclusions

In this paper, to improve the efficiency and applicability of the ECO system, we proposed a heterogeneous MCDM method to deal with the sustainable supplier selection problem with multiple information formats and verified it using a practical example. To better express the ambiguity and uncertainties inherent in the assessment information, heterogeneous types of information were used to represent the evaluation values under different criteria and by applying the TOPSIS-based method, heterogeneous assessment information was aggregated into IVIFNs. We extended the TODIM method to an IVIF context and employed it to achieve the ranking order of the alternative suppliers.

Using a practical case, we compared the proposed method with some previous methods to illustrate the application and advantages of the proposed sustainable supplier evaluation method. We found that our proposed method selected the same optimal sustainable supplier and the least favorable supplier as the two comparative approaches, which shows the validity of the proposed model. Secondly, the proposed method distinguished the sustainability performance of these two suppliers by ranking, but the weighted average method delivered the same ranks. In addition, the fuzzy TOPSIS method had inconsistencies in the ranking results but the proposed heterogeneous MCDM was able to derive a ranking result that was closer to the real situation.

The proposed method also has several limitations, some of which may be addressed by future research development. Each industry has its own characteristics and focus on sustainability, which are constraints and research priorities for future research. First, the proposed supplier evaluation methodology should be altered and improved when applied in diverse industries. Secondly, the evaluation criteria were assumed to be independent in the proposed method, while in many real cases, the criteria are interactive with each other. Thus, it was suggested that a modified method should be developed to deal with the interdependence of evaluation criteria. Third, we indicated that in future research we could insert the evaluation of supplier sustainability performance in an integral model, which would provide a more complete and comprehensive assessment of the overall performance of the supplier. In addition, we highlighted that the evaluations must be constant, and therefore it is necessary to select criteria from which information can be obtained continuously over time. Last but not least, we should further consider the possibility of inserting supplier evaluation methodologies within a more global framework built on artificial intelligence applied to organizations.

In conclusion, this paper mainly contributes to the existing sustainability literature in two aspects. First, the effectiveness of heterogeneous expression domains of preferences in dealing with the uncertainty involved in the assessment information and differentiating the nature of evaluation criteria was demonstrated in this work. Secondly, the TODIM method was extended to process the assessment information in the form of IVIFNs, which can derive a more accurate and distinctive ranking result by considering the decision makers' behavior.

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