Green Supplier Evaluation and Selection Using Interval 2-Tuple Linguistic Hybrid Aggregation Operators

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Abstract. In this paper, we investigate green supplier evaluation and selection problems within the interval 2-tuple linguistic environment. Based on the operational laws and comparison rule of interval 2-tuple linguistic variables, we develop some new aggregation operators, such as the interval 2-tuple hybrid averaging (ITHA) operator, the interval 2-tuple ordered weighted averaging-weighted averaging (ITOWAWA) operator and the interval 2-tuple hybrid geometric (ITHG) operator. Then, an approach for green supplier evaluation and selection under the context of interval 2-tuple linguistic variables is proposed based on the developed interval 2-tuple linguistic hybrid aggregation operators. Finally, a practical application to the green supplier selection problem of an automobile manufacturer is presented to reveal the potentiality and aptness of the proposed green supplier selection approach. According to the findings, the supplier number 'five' got the highest rank, out of the five alternative green suppliers. The approach proposed in this paper may help managers and business professionals to evaluate and select the optimal green supplier by considering the importance degrees of both the given arguments and their ordered positions. Furthermore, it is able to take different scenarios into account and provide a more complete picture to the decision maker by using different hybrid aggregation operators.

Key words: green supply chain management, supplier selection, interval 2-tuple linguistic variables, aggregation operator.

1. Introduction

Supply chain management (SCM) is a process of systematizing and amalgamating diverse activities, starting from customers' order to end product delivery in a well-organized manner (Kahraman *et al.*, 2014). The success of an SCM largely depends upon a suitable system and appropriate suppliers. Thus, organizations must try their hard to advance operational performance to stay competitive in the global marketplace by selecting the most suitable partner (Karsak and Dursun, 2015; Keshavarz Ghorabaee *et al.*, 2017b;

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Wen *et al.*, 2016). Supplier evaluation and selection is the essential core of the SCM, which can significantly reduce operating costs and improve organizational competitiveness to develop business opportunities (Dursun and Karsak, 2014; Kannan *et al.*, 2013; Zhao *et al.*, 2017). Moreover, with increasing concern towards the shortage of resources and environmental pollution, it becomes more important to pay attention to environmental requirements and evaluating potential suppliers by incorporating green factors into the selection process (Fallahpour *et al.*, 2017a; Keshavarz Ghorabaee *et al.*, 2017b; Shi *et al.*, 2018; Zavadskas *et al.*, 2016b).

Because green supplier is located upstream of an entire supply chain, it can improve the compatibility of a supply chain effectively and impact the environmental performance of a manufacturer greatly. Green supplier selection can be considered as a kind of multiple criteria decision making (MCDM) problem that involves many qualitative and quantitative evaluation criteria, such as resource consumption, green image, green competencies, and product life cycle cost (Cao *et al.*, 2015; Govindan *et al.*, 2015; Keshavarz Ghorabaee *et al.*, 2017a). In practice, most of the detailed evaluation information is not known and many factors are impacted by uncertainty (Wu *et al.*, 2016; Yang *et al.*, 2017; Zhong and Yao, 2017). As a result, decision makers tend to express their judgements on the green performance of alternative suppliers based on linguistic expressions (Martínez and Herrera, 2012; Qin and Liu, 2016). Moreover, due to information insufficiency or professional restriction, experts may have difficulties in giving their assessments by simple linguistic terms. Instead, they often doubt among different linguistic terms or require complex linguistic expressions to represent their opinions accurately (Santos *et al.*, 2017; Senthil *et al.*, 2014; Zhang and Guo, 2016). In such cases, the interval 2-tuple linguistic model suggested by Zhang (2012) could be considered a useful tool for handling higher uncertainty in the green supplier selection problems. It is an extension of the 2-tuple linguistic method (Herrera and Martínez, 2000) and established using the concept of symbolic translation (Li and Liu, 2015). The interval 2-tuple linguistic method can not only deal with decision makers' uncertain linguistic information effectively, but also avoid information distortion and loss in the process of linguistic computing. Hence, the concept of interval 2-tuple linguistic variables has received increasing attention since its inception (Liu *et al.*, 2016; Lu *et al.*, 2016; Wang *et al.*, 2017; You *et al.*, 2015).

To aggregate the interval 2-tuple linguistic information in the decision making process, Zhang (2012) introduced several interval 2-tuple linguistic aggregation operators, which include the interval 2-tuple weighted average (ITWA) operator and the interval 2-tuple ordered weighted average (ITOWA) operator. Zhang (2013) further developed the interval 2-tuple weighted geometric (ITWG) operator, the interval 2-tuple ordered weighted geometric (ITOWG) operator, the generalized interval 2-tuple weighted average (GITWA) operator and the generalized interval 2-tuple ordered weighted average (GITOWA) operator. The authors also established some desirable properties of the proposed operators and analysed the relations among them. We know that the ITWA and the ITWG operators weight only the interval 2-tuples, while the ITOWA and the ITOWG operators weight only the ordered positions of the interval 2-tuples instead of weighting the interval 2-tuples themselves. Consequently, weights denote different characteristics in the ITWA (ITWG)

and the ITOWA (ITOWG) operators. Nevertheless, only one of them is taken into account in the two types of operators. Therefore, it is justifiable to extend the hybrid averaging (HA) operator (Xu and Da, 2003), the ordered weighted averaging-weighted averaging (OWAWA) operator (Merigó, 2011) as well as the hybrid geometric (HG) operator (Xu and Da, 2003) to accommodate the situations where the input arguments are interval 2-tuple linguistic variables.

Against the above background, the intent of this paper is to develop a green supplier evaluation and selection framework based on interval 2-tuple linguistic hybrid aggregation operators to evaluate and determine the most appropriate green supplier in the presence of uncertainty. This research contributes to the literature in the following three dimensions. First, we propose some new aggregation operators, i.e. the interval 2-tuple hybrid averaging (ITHA) operator, the interval 2-tuple ordered weighted averaging-weighted averaging (ITOWAWA) operator and the interval 2-tuple hybrid geometric (ITHG) operator, by considering the weights of the given arguments and their ordered positions. Second, a decision making approach is introduced for handling the green supplier selection problems with interval 2-tuple linguistic information. Third, we utilize an application example in an automobile manufacturing company to show the feasibility and practicality of the proposed green supplier selection approach. Towards this end, the remaining part of this paper is organized as follows: Section 2 presents a brief review of literature on green supplier selection methods and interval 2-tuple linguistic aggregation operators. Section 3 introduces some basic concepts and operational laws related to the interval 2-tuple linguistic method. In Section 4, we propose the interval 2-tuple linguistic hybrid aggregation operators, including the ITHA operator, the ITOWAWA operator and the ITHG operator. In Section 5, we apply the developed operators to deal with green supplier evaluation and selection problems within the interval 2-tuple linguistic environment. A practical case is given in Section 6 to explain the effectiveness and usefulness of the proposed green supplier selection approach. Finally, we conclude this paper and give future directions in Section 7.

2. Related Literature

In this section, we mainly review the related literature on green supplier selection methods and interval 2-tuple linguistic aggregation operators.

2.1. *Green Supplier Selection Methods*

In recent years, researchers have presented many decision making approaches and techniques for the selection of optimal green suppliers (Mardani *et al.*, 2015b; Zavadskas *et al.*, 2016a). For example, Yazdani *et al.* (2017) proposed a combined model for choosing suitable green suppliers by using decision-making trial and evaluation laboratory (DEMA-TEL), quality function deployment (QFD), and complex proportional assessment (CO-PRAS) methods. Qin *et al.* (2017) extended the TODIM (an acronym in Portuguese of interactive and multi-criteria decision making) method to accommodate interval type-2

fuzzy environment and further presented a green supplier selection method based on decision maker's bounded rationality behaviour. Wang *et al.* (2017) put forward an integrated MCDM approach which combines cloud model and QUALIFLEX (qualitative flexible multiple criteria method) approach to evaluate the green performance of corporations with economic and environmental criteria. Luthra *et al.* (2017) used an integrated analytical hierarchy process (AHP) and VIKOR (ViseKriterijumska Optimizacija I Kompromisno Resenje) method for the evaluation and selection of sustainable suppliers. Fallahpour *et al.* (2017a) developed a hybrid hierarchical decision support model for sustainable supplier selection by integrating fuzzy preference programming with fuzzy technique for order of preference by similarity to ideal solution (TOPSIS) approach. Bakeshlou *et al.* (2017) employed a hybrid fuzzy multi objective decision making (MODM) model to solve the green supplier selection problem, in which DEMATEL was used to understand the interrelations among criteria and fuzzy ANP provided their weights with respect to the dependencies. Keshavarz Ghorabaee *et al.* (2016) proposed an integrated approach based on weighted aggregated sum product assessment (WASPAS) method and interval type-2 fuzzy sets for the multi-criteria evaluation of green suppliers. In Liao *et al.* (2016), the authors integrated fuzzy AHP, fuzzy additive ratio assessment (ARAS-F) and multi-segment goal programming (MSGP) methods to address green supplier selection problems. In Liou *et al.* (2016), a hybrid framework was reported for determining the best supplier in the green supply chain, in which DEMATEL-based ANP (DANP) was used to address the dependent relationships between criteria and COPRAS with grey relations (COPRAS-G) was utilized for the ranking of green suppliers. For other green supplier evaluation and selection methods, please refer to the reviewer papers of Govindan *et al.* (2015) and Mardani *et al.* (2015a).

2.2. *Interval 2-Tuple Linguistic Aggregation Operators*

In recent years, many interval 2-tuple linguistic aggregation operators have been developed since information aggregation plays a large role in the decision making process. For instance, Shan *et al.* (2016a) developed some interval 2-tuple linguistic distance operators such as the interval 2-tuple weighted distance, the interval 2-tuple ordered weighted distance, and the interval 2-tuple hybrid weighted distance operators for supplier evaluation and selection. Shan *et al.* (2016b) proposed some interval 2-tuple linguistic aggregation operators called the interval 2-tuple hybrid harmonic mean operator, the induced interval 2-tuple ordered weighted harmonic mean operator, and the induced interval 2-tuple hybrid harmonic mean operator for coping with material selection problems. To deal with the situation where the elements in a set are interdependent, Meng *et al.* (2016) defined several generalized interval 2-tuple linguistic correlated aggregation operators with the aid of Choquet integral and the generalized Shapley function. Considering the interrelationships among input arguments, Liu *et al.* (2016) put forward some interval 2-tuple linguistic Bonferroni mean operators to manage multiple attributes group decision making problems. Lu *et al.* (2016) introduced the interval 2-tuple induced ordered weighted distance operator and proposed an interval 2-tuple induced TOPSIS method for the assessment of

health-care waste treatment techniques. Tao *et al.* (2017) presented some closed algebra operational laws for interval linguistic labels and developed some extended t-norms and s-norms based interval linguistic weighted power average operators for linguistic decision making. Wei and Liao (2016) proposed the multigranularity hesitant 2-tuple weighted average operator, the multigranularity hesitant 2-tuple ordered weighted average operator, and the multigranularity hesitant 2-tuple weighted ordered weighted average operator for multigranularity linguistic group decision making. In addition, the interval 2-tuple linguistic generalized power average operator and the interval 2-tuple linguistic generalized power ordered weighted average operator were proposed by Wu *et al.* (2015); the interval 2-tuple correlated averaging operator and the interval 2-tuple correlated geometric operator were presented by Wang *et al.* (2015); the generalized interval 2-tuple linguistic Shapley chi-square averaging operator was proposed by Lin *et al.* (2015); and the interval 2-tuple correlated averaging operator, the interval 2-tuple correlated geometric operator, and the generalized interval 2-tuple correlated averaging operator were proposed by Beg and Rashid (2014).

The literature review above shows that a variety of methods have been proposed by researchers to resolve the issue of evaluating and ranking green suppliers. However, little attention has been paid to the interval 2-tuple linguistic method for assessing suppliers' green performance in the presence of uncertainty. The interval 2-tuple linguistic ELECTRE II (Wang *et al.*, 2017) and the interval 2-tuple linguistic VIKOR (You *et al.*, 2015) methods were proposed for supplier selection in the interval 2-tuple linguistic environment, yet green criteria are not taken into account in these studies in evaluating the overall performance of suppliers. On the other hand, while a lot of interval 2-tuple linguistic aggregation operators have been proposed in the existing references, to the best of our knowledge, all these operators consider only the ordered positions of arguments or the given importance of arguments. Therefore, in this study, we first develop some interval 2-tuple linguistic hybrid aggregation operators (i.e. the ITHA operator, the ITOWAWA operator and the ITHG operator) to reflect both the given importance and ordered position of the argument. Next, based on these operators, a new approach is proposed to manage the green supplier evaluation and selection problems with interval 2-tuple linguistic information. The incorporation of interval 2-tuple linguistic theory into the multi-criteria green supply selection method would allow for effective qualitative assessment and decision making when insufficient quantitative data is available.

3. Preliminaries

In this section, some basic definitions and notations concerning 2-tuple linguistic variables and interval 2-tuple linguistic variables are presented.

3.1. *2-Tuple Linguistic Variables*

Linguistic variables are able to deal with the circumstances which are too complex or too ill-defined to be handled using the traditional quantitative expressions (Zadeh, 1975). For

facilitating computation, it is required that linguistic terms have the characteristics of finite set, odd cardinality, semantic symmetric, ordinal level and compensative operation. For a linguistic term set $S = \{s_0, s_1, \ldots, s_g\}$, where s_i represents a possible value for a linguistic variable, the following characteristics should be satisfied (Herrera and Martínez, 2000; Liu *et al.*, 2014):

    (1) Negation operator: $\text{Neg}(s_i) = s_j$ such that $j = g - i$;

    (2) The set is ordered: $s_i > s_j$, if $i > j$;

    (3) Max operator: $\max(s_i, s_j) = s_i$, if $s_i \geqslant s_j$.

The 2-tuple linguistic method was firstly proposed in Herrera and Martínez (2000) based on the concept of symbolic translation. The linguistic information is represented by a linguistic 2-tuple, (s_i, α), where s_i is a linguistic term from the linguistic term set S and α is a numerical value representing the symbolic translation. Later, Tai and Chen (2009) presented a generalized 2-tuple linguistic model to overcome the restriction of linguistic 2-tuples.

DEFINITION 1. Let $S = \{s_0, s_1, \ldots, s_g\}$ be a linguistic term set and $\beta \in [0, 1]$ be the result of a symbolic aggregation operation. The following translation function Δ is defined to determine the 2-tuple linguistic value equivalent to β (Tai and Chen, 2009):

$$\Delta : [0, 1] \to S \times \left[-\frac{1}{2g}, \frac{1}{2g} \right), \tag{1}$$

$$\Delta(\beta) = (s_i, \alpha), \quad \text{with} \quad \begin{cases} s_i, & i = \text{round}(\beta \cdot g), \\ \alpha = \beta - \frac{i}{g}, & \alpha \in [-\frac{1}{2g}, \frac{1}{2g}), \end{cases} \tag{2}$$

where $\text{round}(\cdot)$ is the usual rounding operation and α is the value of symbolic translation.

DEFINITION 2. Let $S = \{s_0, s_1, \ldots, s_g\}$ be a linguistic term set and (s_i, α) be a 2-tuple. To convert a 2-tuple linguistic value into its equivalent numerical value $\beta \in [0, 1]$, the reverse function Δ^{-1} is defined as follows (Tai and Chen, 2009):

$$\Delta^{-1} : S \times \left[-\frac{1}{2g}, \frac{1}{2g} \right) \to [0, 1], \tag{3}$$

$$\Delta^{-1}(s_i, \alpha) = \frac{i}{g} + \alpha = \beta. \tag{4}$$

It may be mentioned that a linguistic term can be converted into a linguistic 2-tuple by adding a value 0 as symbolic translation (Herrera and Martínez, 2000):

$$s_i \in S \Rightarrow (s_i, 0). \tag{5}$$

3.2. *Interval 2-Tuple Linguistic Variables*

Based on the definitions of Tai and Chen (2009), Zhang (2012) put forward an interval 2-tuple linguistic representation model as a generalization of the 2-tuple linguistic variables.

DEFINITION 3. Let $S = \{s_0, s_1, \ldots, s_g\}$ be a linguistic term set. An interval 2-tuple linguistic value is denoted by $[(s_i, \alpha_i), (s_j, \alpha_j)]$, where $(s_i, \alpha_i) \leqslant (s_j, \alpha_j)$. The interval 2-tuple that equals to an interval value $[\beta_1, \beta_2](\beta_1, \beta_2 \in [0, 1], \beta_1 \leqslant \beta_2)$ is derived by the following function (Zhang, 2012, 2013):

$$\Delta[\beta_1, \beta_2] = \big[(s_i, \alpha_i), (s_j, \alpha_j)\big] \quad \text{with} \quad \begin{cases} s_i, & i = \text{round}(\beta_1 \cdot g), \\ s_j, & j = \text{round}(\beta_2 \cdot g), \\ \alpha_i = \beta_1 - \frac{i}{g}, & \alpha_i \in \big[-\frac{1}{2g}, \frac{1}{2g}\big), \\ \alpha_j = \beta_2 - \frac{j}{g}, & \alpha_j \in \big[-\frac{1}{2g}, \frac{1}{2g}\big). \end{cases} \tag{6}$$

Otherwise, there exists a function Δ^{-1} that can transform an interval 2-tuple into an interval value $[\beta_1, \beta_2](\beta_1, \beta_2 \in [0, 1], \beta_1 \leqslant \beta_2)$ by Zhang (2012, 2013):

$$\Delta^{-1}\big[(s_i, \alpha_i), (s_j, \alpha_j)\big] = \left[\frac{i}{g} + \alpha_i, \frac{j}{g} + \alpha_j\right] = [\beta_1, \beta_2]. \tag{7}$$

Especially, if $(s_i, \alpha_i) = (s_j, \alpha_j)$, then the interval 2-tuple linguistic variable reduces to a 2-tuple linguistic variable.

Given any three interval 2-tuples $\tilde{a} = [(s, \alpha), (t, \varepsilon)]$, $\tilde{a}_1 = [(s_1, \alpha_1), (t_1, \varepsilon_1)]$ and $\tilde{a}_2 = [(s_2, \alpha_2), (t_2, \varepsilon_2)]$, and let $\lambda \in [0, 1]$. Then their operational laws are defined as follows (Liu *et al.*, 2014):

(1) $\tilde{a}_1 \otimes \tilde{a}_2 = [(s_1, \alpha_1), (t_1, \varepsilon_1)] \otimes [(s_2, \alpha_2), (t_2, \varepsilon_2)]$
$\qquad = \Delta[\Delta^{-1}(s_1, \alpha_1) \cdot \Delta^{-1}(s_2, \alpha_2), \Delta^{-1}(t_1, \varepsilon_1) \cdot \Delta^{-1}(t_2, \varepsilon_2)];$

(2) $\tilde{a}_1 \oplus \tilde{a}_2 = [(s_1, \alpha_1), (t_1, \varepsilon_1)] \oplus [(s_2, \alpha_2), (t_2, \varepsilon_2)]$
$\qquad = \Delta[\Delta^{-1}(s_1, \alpha_1) + \Delta^{-1}(s_2, \alpha_2), \Delta^{-1}(t_1, \varepsilon_1) + \Delta^{-1}(t_2, \varepsilon_2)];$

(3) $\tilde{a}^\lambda = ([(s, \alpha), (t, \varepsilon)])^\lambda = \Delta[(\Delta^{-1}(s, \alpha))^\lambda, (\Delta^{-1}(t, \varepsilon))^\lambda];$

(4) $\lambda\tilde{a} = \lambda[(s, \alpha), (t, \varepsilon)] = \Delta[\lambda\Delta^{-1}(s, \alpha), \lambda\Delta^{-1}(t, \varepsilon)].$

The comparison of linguistic information represented by interval 2-tuples is implemented on the basis of the degree of possibility of interval 2-tuple linguistic variables.

DEFINITION 4. Let $\tilde{a}_1 = [(s_1, \alpha_1), (t_1, \varepsilon_1)]$ and $\tilde{a}_2 = [(s_2, \alpha_2), (t_2, \varepsilon_2)]$ be two interval 2-tuples and let $h(\tilde{a}_1) = \Delta^{-1}(t_1, \varepsilon_1) - \Delta^{-1}(s_1, \alpha_1) = \delta_1 - \beta_1$ and $h(\tilde{a}_2) = \Delta^{-1}(t_2, \varepsilon_2) - \Delta^{-1}(s_2, \alpha_2) = \delta_2 - \beta_2$, then the degree of possibility of $\tilde{a}_1 \geqslant \tilde{a}_2$ is computed as (Liu *et al.*, 2014):

$$p(\tilde{a}_1 \geqslant \tilde{a}_2) = \max\left\{1 - \max\left(\frac{\delta_2 - \beta_1}{h(\tilde{a}_1) + h(\tilde{a}_2)}, 0\right), 0\right\}. \tag{8}$$

Similarly, the degree of possibility of $\tilde{a}_2 \geqslant \tilde{a}_1$ is defined as (Liu *et al.*, 2014):

$$p(\tilde{a}_2 \geqslant \tilde{a}_1) = \max\left\{1 - \max\left(\frac{\delta_1 - \beta_2}{h(\tilde{a}_1) + h(\tilde{a}_2)}, 0\right), 0\right\}. \tag{9}$$

From Definition 4, the following useful results can be obtained:

(1) $0 \leqslant p(\tilde{a}_1 \geqslant \tilde{a}_2) \leqslant 1, 0 \leqslant p(\tilde{a}_2 \geqslant \tilde{a}_1) \leqslant 1$;
(2) $p(\tilde{a}_1 \geqslant \tilde{a}_2) + p(\tilde{a}_2 \geqslant \tilde{a}_1) = 1$. Especially, $p(\tilde{a}_1 \geqslant \tilde{a}_1) = p(\tilde{a}_2 \geqslant \tilde{a}_2) = 0.5$.

To rank n interval 2-tuple linguistic arguments $\tilde{a}_i$ $(i = 1, 2, \ldots, n)$, we can compare each argument $\tilde{a}_i$ with all arguments $\tilde{a}_j$ $(j = 1, 2, \ldots, n)$ first with Eq. (8), and let $p_{ij} = p(\tilde{a}_i \geqslant \tilde{a}_j)$. Then a complementary matrix $P = (p_{ij})_{n \times n}$ is constructed, where $p_{ij} \geqslant 0$, $p_{ij} + p_{ji} = 1$, $p_{ii} = 0.5$ $(i, j = 1, 2, \ldots, n)$. By summing all elements in each line of the matrix P, we have $p_i = \sum_{j=1}^{n} p_{ij}$ $(i = 1, 2, \ldots, n)$. Finally, we can rank the arguments $\tilde{a}_i$ $(i = 1, 2, \ldots, n)$ based on the values of p_i $(i = 1, 2, \ldots, n)$ in descending order.

4. Interval 2-Tuple Linguistic Hybrid Aggregation Operators

This section develops some interval 2-tuple linguistic hybrid aggregation operators including the interval 2-tuple hybrid averaging (ITHA) operator, the interval 2-tuple ordered weighted averaging-weighted averaging (ITOWAWA) operator and the interval 2-tuple hybrid geometric (ITHG) operator.

4.1. *Interval 2-Tuple Hybrid Averaging Operators*

DEFINITION 5. Let $\tilde{a}_i = [(s_i, \alpha_i), (t_i, \varepsilon_i)]$ $(i = 1, 2, \ldots, n)$ be a set of interval 2-tuples and $w = (w_1, w_2, \ldots, w_n)^T$ be their associated weights, with $w_i \in [0, 1]$, $\sum_{i=1}^{n} w_i = 1$. The interval 2-tuple weighted average (ITWA) operator is defined as (Zhang, 2012):

$$
\begin{aligned}
\text{ITWA}_w(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) &= \bigoplus_{i=1}^{n}(w_i \tilde{a}_i) \\
&= \Delta\left[\sum_{i=1}^{n} w_i \Delta^{-1}(s_i, \alpha_i), \sum_{i=1}^{n} w_i \Delta^{-1}(t_i, \varepsilon_i)\right].
\end{aligned} \tag{10}
$$

DEFINITION 6. Let $\tilde{a}_i = [(s_i, \alpha_i), (t_i, \varepsilon_i)]$ $(i = 1, 2, \ldots, n)$ be a set of interval 2-tuples and $\omega = (\omega_1, \omega_2, \ldots, \omega_n)^T$ be an associated weight vector, with $\omega_j \in [0, 1]$, $\sum_{j=1}^{n} \omega_j = 1$. The interval 2-tuple ordered weighted average (ITOWA) operator is defined as (Zhang, 2012):

$$
\begin{aligned}
\text{ITOWA}_\omega(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) &= \bigoplus_{j=1}^{n}(\omega_j \tilde{a}_{\sigma(j)}) \\
&= \Delta\left[\sum_{j=1}^{n} \omega_j \Delta^{-1}(s_{\sigma(j)}, \alpha_{\sigma(j)}), \sum_{j=1}^{n} \omega_j \Delta^{-1}(t_{\sigma(j)}, \varepsilon_{\sigma(j)})\right],
\end{aligned} \tag{11}
$$

where $(\sigma(1), \sigma(2), \ldots, \sigma(n))$ is a permutation of $(1, 2, \ldots, n)$, such that $\tilde{a}_{\sigma(j-1)} \geqslant \tilde{a}_{\sigma(j)}$ for all $j = 2, \ldots, n$.

The ITWA operator weights only the input interval 2-tuple arguments, whereas the ITOWA operator weights only the ordered positions of the interval 2-tuple arguments. Therefore, we can see that weights denote different features in the ITWA and the ITOWA operators. However, both the operators only take one of them into account. To solve this drawback, an ITHA operator is proposed in the following part.

DEFINITION 7. Let $\tilde{a}_i = [(s_i, \alpha_i), (t_i, \varepsilon_i)]$ $(i = 1, 2, \ldots, n)$ be a set of interval 2-tuples and $\omega = (\omega_1, \omega_2, \ldots, \omega_n)^T$ be an associated weight vector, with $\omega_j \in [0, 1]$ and $\sum_{j=1}^n \omega_j = 1$. The ITHA operator is defined by

$$\text{ITHA}_{\omega, w}(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) = \bigoplus_{j=1}^n (\omega_j \dot{\tilde{a}}_{\sigma(j)})$$

$$= \Delta \left[\sum_{j=1}^n \omega_j \Delta^{-1}(\dot{s}_{\sigma(j)}, \dot{\alpha}_{\sigma(j)}), \sum_{j=1}^n \omega_j \Delta^{-1}(\dot{t}_{\sigma(j)}, \dot{\varepsilon}_{\sigma(j)}) \right]. \tag{12}$$

where $\dot{\tilde{a}}_{\sigma(j)}$ is the jth largest of the weighted interval 2-tuples $\dot{\tilde{a}}_i (\dot{\tilde{a}}_i = nw_i \tilde{a}_i, i = 1, 2, \ldots, n)$, $w = (w_1, w_2, \ldots, w_n)^T$ be the weights of $\tilde{a}_i$ $(i = 1, 2, \ldots, n)$, with $w_i \in [0, 1]$, $\sum_{i=1}^n w_i = 1$, and n is the balancing coefficient. Let $\omega = (1/n, 1/n, \ldots, 1/n)$, then the ITWA operator is a special case of the ITHA operator. Let $w = (1/n, 1/n, \ldots, 1/n)$, then the ITOWA operator is a special case of the ITHA operator.

EXAMPLE 1. Assume $S = \{s_0, s_1, \ldots, s_6\}$ be a linguistic term set, $\omega = (0.1, 0.4, 0.4, 0.1)^T$, $w = (0.2, 0.3, 0.2, 0.3)^T$, $\tilde{a}_1 = [(s_1, 0), (s_2, 0)]$, $\tilde{a}_2 = [(s_3, 0), (s_5, 0)]$, $\tilde{a}_3 = [(s_2, 0), (s_4, 0)]$, and $\tilde{a}_4 = [(s_4, 0), (s_6, 0)]$. By Definition 7, we have

$$\dot{\tilde{a}}_1 = 4 \times 0.2 \times \big[(s_1, 0), (s_2, 0)\big] = \big[(s_1, -0.033), (s_2, -0.067)\big],$$

$$\dot{\tilde{a}}_2 = 4 \times 0.3 \times \big[(s_3, 0), (s_5, 0)\big] = \big[(s_4, -0.067), (s_6, 0)\big],$$

$$\dot{\tilde{a}}_3 = 4 \times 0.2 \times \big[(s_2, 0), (s_4, 0)\big] = \big[(s_2, -0.067), (s_3, 0.033)\big],$$

$$\dot{\tilde{a}}_4 = 4 \times 0.3 \times \big[(s_4, 0), (s_6, 0)\big] = \big[(s_5, -0.033), (s_7, 0.033)\big].$$

Based on the comparison method of interval 2-tuples, we have

$$p_1 = 0.500, \qquad p_2 = 2.750, \qquad p_3 = 1.500, \qquad p_4 = 3.250.$$

Then we rank the arguments $\dot{\tilde{a}}_i$ $(i = 1, 2, 3, 4)$ in descending order according to the values of p_i $(i = 1, 2, 3, 4)$:

$$\dot{\tilde{a}}_{\sigma(1)} = \dot{\tilde{a}}_4 = \big[(s_5, -0.033), (s_7, 0.033)\big], \quad \dot{\tilde{a}}_{\sigma(2)} = \dot{\tilde{a}}_2 = \big[(s_4, -0.067), (s_6, 0)\big],$$

$$\dot{\tilde{a}}_{\sigma(3)} = \dot{\tilde{a}}_3 = \big[(s_2, -0.067), (s_3, 0.033)\big], \quad \dot{\tilde{a}}_{\sigma(4)} = \dot{\tilde{a}}_1 = \big[(s_1, -0.033), (s_2, -0.067)\big].$$

Thus,

$$\text{ITHA}_{\omega,w}(\tilde{a}_1, \tilde{a}_2, \tilde{a}_3, \tilde{a}_4)$$

$$= 0.1 \times \big[(s_5, -0.033), (s_7, 0.033)\big] \oplus 0.4 \times \big[(s_4, -0.067), (s_6, 0)\big]$$

$$\oplus 0.4 \times \big[(s_2, -0.067), (s_3, 0.033)\big] \oplus 0.1 \times \big[(s_1, -0.033), (s_2, -0.067)\big]$$

$$= \Delta[0.440, 0.760] = \big[(s_3, -0.060), (s_5, -0.073)\big].$$

The ITHA operator arrives to a unification between the ITWA and the ITOWA operators because both concepts are included in the formulation as particular cases. However, the model can unify them but it cannot consider how relevant these concepts are in a specific problem considered. For example, in some problems we may prefer to give more importance to the ITOWA operator because we believe that it is more relevant and vice versa. To overcome this issue, in the following we present an ITOWAWA operator.

DEFINITION 8.　Let $\tilde{a}_i = [(s_i, \alpha_i), (t_i, \varepsilon_i)]$ $(i = 1, 2, \ldots, n)$ be a set of interval 2-tuples and $\omega = (\omega_1, \omega_2, \ldots, \omega_n)^T$ be an associated weight vector, with $\omega_j \in [0, 1]$, $\sum_{j=1}^{n} \omega_j = 1$. The ITOWAWA operator is defined as

$$\text{ITOWAWA}_{\omega,w}(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) = \bigoplus_{j=1}^{n} (v_j \tilde{a}_{\sigma(j)})$$

$$= \Delta \left[\sum_{j=1}^{n} v_j \Delta^{-1}(s_{\sigma(j)}, \alpha_{\sigma(j)}), \sum_{j=1}^{n} v_j \Delta^{-1}(t_{\sigma(j)}, \varepsilon_{\sigma(j)}) \right], \tag{13}$$

where $\tilde{a}_{\sigma(j)}$ is the jth largest of the $\tilde{a}_i$, each argument $\tilde{a}_i$ has an associated weight w_i with $w_i \in [0, 1]$, $\sum_{i=1}^{n} w_i = 1$, $v_j = \phi \omega_j + (1 - \phi) w_j$ with $\phi \in [0, 1]$, and w_j is the weight w_i ordered according to $\tilde{a}_{\sigma(i)}$, that is, according to the jth largest of the $\tilde{a}_i$. As we can see, if $\phi = 1$, we get the ITOWA operator and if $\phi = 0$, the ITWA is obtained.

It is worthwhile to point out that we can formulate the ITOWAWA operator by separating the part that strictly affects the ITOWA operator and the part that affects the ITWA operator.

DEFINITION 9.　Let $\tilde{a}_i = [(s_i, \alpha_i), (t_i, \varepsilon_i)]$ $(i = 1, 2, \ldots, n)$ be a set of interval 2-tuples, $\omega = (\omega_1, \omega_2, \ldots, \omega_n)^T$ be an associated weight vector, with $\omega_j \in [0, 1]$, $\sum_{j=1}^{n} \omega_j = 1$, and $w = (w_1, w_2, \ldots, w_n)^T$ be the weights of $\tilde{a}_i$ $(i = 1, 2, \ldots, n)$, with $w_i \in [0, 1]$, $\sum_{i=1}^{n} w_i = 1$. The ITOWAWA operator can be rewritten as

$$\text{ITOWAWA}_{\omega,w}(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) = \phi \bigoplus_{j=1}^{n} (\omega_j \tilde{a}_{\sigma(j)}) \oplus (1 - \phi) \bigoplus_{i=1}^{n} (w_i \tilde{a}_i), \tag{14}$$

where $\tilde{a}_{\sigma(j)}$ is the jth largest of the $\tilde{a}_i$, and $\phi \in [0, 1]$.

The key benefit of the ITOWAWA operator is that it combines the ITOWA and the ITWA operators considering the importance degree of each concept in the formulation. Therefore, in the real application, it is possible to give more or less importance to the ITOWA operator or the ITWA operator depending on our interests on the problem analysed.

EXAMPLE 2. Assume $S = \{s_0, s_1, \ldots, s_6\}$ be a linguistic term set, $\omega = (0.2, 0.2, 0.3, 0.3)^T$, $w = (0.3, 0.2, 0.4, 0.1)^T$, $\tilde{a}_1 = [(s_2, 0), (s_2, 0)]$, $\tilde{a}_2 = [(s_3, 0), (s_4, 0)]$, $\tilde{a}_3 = [(s_2, 0), (s_3, 0)]$, and $\tilde{a}_4 = [(s_4, 0), (s_5, 0)]$. It is worth stressing that the ITOWA has an importance degree of 40% while the ITWA has an importance degree of 60%. Similar to Example 2, we rank the arguments $\tilde{a}_i$ $(i = 1, 2, 3, 4)$ in descending order based on the values of p_i $(i = 1, 2, 3, 4)$:

$$\tilde{a}_{\sigma(1)} = \tilde{a}_4 = [(s_4, 0), (s_5, 0)], \qquad \tilde{a}_{\sigma(2)} = \tilde{a}_2 = [(s_3, 0), (s_4, 0)],$$
$$\tilde{a}_{\sigma(3)} = \tilde{a}_3 = [(s_2, 0), (s_3, 0)], \qquad \tilde{a}_{\sigma(4)} = \tilde{a}_1 = [(s_2, 0), (s_2, 0)].$$

With Eq. (13), the new weight vector is calculated as

$$v_1 = 0.4 \times 0.2 + 0.6 \times 0.1 = 0.14, \qquad v_2 = 0.4 \times 0.2 + 0.6 \times 0.2 = 0.2,$$
$$v_3 = 0.4 \times 0.3 + 0.6 \times 0.4 = 0.36, \qquad v_4 = 0.4 \times 0.3 + 0.6 \times 0.3 = 0.3.$$

Thus,

$$\begin{aligned}
&\text{ITOWAWA}_{\omega, w}(\tilde{a}_1, \tilde{a}_2, \tilde{a}_3, \tilde{a}_4) \\
&= 0.14 \times [(s_4, 0), (s_5, 0)] \oplus 0.2 \times [(s_3, 0), (s_4, 0)] \oplus 0.36 \\
&\quad \times [(s_2, 0), (s_3, 0)] \oplus 0.3 \times [(s_2, 0), (s_2, 0)] \\
&= \Delta[0.413, 0.530] = [(s_2, 0.080), (s_3, 0.030)].
\end{aligned}$$

With Eq. (14), we aggregate the four arguments as follows:

$$\begin{aligned}
&\text{ITOWAWA}_{\omega, w}(\tilde{a}_1, \tilde{a}_2, \tilde{a}_3, \tilde{a}_4) \\
&= 0.4 \times \big(0.2 \times [(s_4, 0), (s_5, 0)] \oplus 0.2 \times [(s_3, 0), (s_4, 0)] \oplus 0.3 \\
&\quad \times [(s_2, 0), (s_3, 0)] \oplus 0.3 \times [(s_2, 0), (s_2, 0)]\big) \oplus 0.6 \\
&\quad \times \big(0.3 \times [(s_2, 0), (s_2, 0)] \oplus 0.2 \times [(s_3, 0), (s_4, 0)] \oplus 0.4 \\
&\quad \times [(s_2, 0), (s_3, 0)] \oplus 0.1 \times [(s_4, 0), (s_5, 0)]\big) \\
&= \Delta[0.413, 0.530] = [(s_2, 0.080), (s_3, 0.030)].
\end{aligned}$$

From the above computations, it can be observed that the same results are derived with both methods.

4.2. *Interval 2-Tuple Hybrid Geometric Operators*

DEFINITION 10. Let $\tilde{a}_i = [(s_i, \alpha_i), (t_i, \varepsilon_i)]$ $(i = 1, 2, \ldots, n)$ be a set of interval 2-tuples and $w = (w_1, w_2, \ldots, w_n)^T$ be their associated weights, with $w_i \in [0, 1]$ and $\sum_{i=1}^{n} w_i = 1$. The interval 2-tuple weighted geometric (ITWG) operator is obtained by Zhang (2013):

$$\mathrm{ITWG}_w(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) = \bigotimes_{i=1}^{n} (\tilde{a}_i)^{w_i}$$

$$= \Delta \left[\prod_{i=1}^{n} \left(\Delta^{-1}(s_i, \alpha_i) \right)^{w_i}, \prod_{i=1}^{n} \left(\Delta^{-1}(t_i, \varepsilon_i) \right)^{w_i} \right]. \tag{15}$$

DEFINITION 11. Let $\tilde{a}_i = [(s_i, \alpha_i), (t_i, \varepsilon_i)]$ $(i = 1, 2, \ldots, n)$ be a set of interval 2-tuples and be an associated weight vector, with $\omega_j \in [0, 1]$, $\sum_{j=1}^{n} \omega_j = 1$. The interval 2-tuple ordered weighted geometric (ITOWG) operator is defined as (Zhang, 2013):

$$\mathrm{ITOWG}_\omega(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) = \bigotimes_{i=1}^{n} (\tilde{a}_{\sigma(j)})^{\omega_j}$$

$$= \Delta \left[\prod_{j=1}^{n} \left(\Delta^{-1}(s_{\sigma(j)}, \alpha_{\sigma(j)}) \right)^{\omega_j}, \prod_{j=1}^{n} \left(\Delta^{-1}(t_{\sigma(j)}, \varepsilon_{\sigma(j)}) \right)^{\omega_j} \right], \tag{16}$$

where $(\sigma(1), \sigma(2), \ldots, \sigma(n))$ is a permutation of $(1, 2, \ldots, n)$, such that $\tilde{a}_{\sigma(j-1)} \geqslant \tilde{a}_{\sigma(j)}$ for all $j = 2, \ldots, n$.

From Definitions 10 and 11, we know that the ITWG operator weights only the interval 2-tuple linguistic variables, while the ITOWG operator weights only the ordered positions of the interval 2-tuple linguistic variables instead of weighting the interval 2-tuples themselves. Therefore, weights represent different aspects in both the ITWG and the ITOWG operators. However, both the operators consider only one of them. To solve this drawback, in the following we propose an ITHG operator.

DEFINITION 12. Let $\tilde{a}_i = [(s_i, \alpha_i), (t_i, \varepsilon_i)]$ $(i = 1, 2, \ldots, n)$ be a set of interval 2-tuples and $\omega = (\omega_1, \omega_2, \ldots, \omega_n)^T$ be an associated weight vector, with $\omega_j \in [0, 1]$, $\sum_{j=1}^{n} \omega_j = 1$. The ITHG operator is defined as

$$\mathrm{ITHG}_{\omega, w}(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) = \bigotimes_{j=1}^{n} (\dot{\tilde{a}}_{\sigma(j)})^{\omega_j}$$

$$= \Delta \left[\prod_{j=1}^{n} \left(\Delta^{-1}(\dot{s}_{\sigma(j)}, \dot{\alpha}_{\sigma(j)}) \right)^{\omega_j}, \prod_{j=1}^{n} \left(\Delta^{-1}(\dot{t}_{\sigma(j)}, \dot{\varepsilon}_{\sigma(j)}) \right)^{\omega_j} \right], \tag{17}$$

where $\dot{\tilde{a}}_{\sigma(j)}$ is the jth largest of the weighted interval 2-tuples $\dot{\tilde{a}}_i (\dot{\tilde{a}}_i = \tilde{a}_i^{n w_i}, i = 1, 2, \ldots, n)$, $w = (w_1, w_2, \ldots, w_n)^T$ be the weights of $\tilde{a}_i$ $(i = 1, 2, \ldots, n)$, with $w_i \in$

$[0, 1]$, $\sum_{i=1}^{n} w_i = 1$, and n is the balancing coefficient. Let $\omega = (1/n, 1/n, \ldots, 1/n)$, then the ITWG operator is a special case of the ITHG operator. Let $w = (1/n, 1/n, \ldots, 1/n)$, then the ITOWG operator is a special case of the ITHG operator.

EXAMPLE 3. Assume $S = \{s_0, s_1, \ldots, s_6\}$ be a linguistic term set, $\omega = (0.1, 0.4, 0.3, 0.2)^T$, $w = (0.2, 0.3, 0.1, 0.4)^T$, $\tilde{a}_1 = [(s_1, 0), (s_3, 0)]$, $\tilde{a}_2 = [(s_4, 0), (s_5, 0)]$, $\tilde{a}_3 = [(s_3, 0), (s_3, 0)]$, and $\tilde{a}_4 = [(s_3, 0), (s_4, 0)]$. By Definition 12, we have

$$\dot{\tilde{a}}_1 = \big[(s_1, 0), (s_3, 0)\big]^{4 \times 0.2} = \big[(s_1, 0.072), (s_3, 0.074)\big],$$

$$\dot{\tilde{a}}_2 = \big[(s_3, 0), (s_5, 0)\big]^{4 \times 0.3} = \big[(s_4, -0.052), (s_5, -0.030)\big],$$

$$\dot{\tilde{a}}_3 = \big[(s_2, 0), (s_4, 0)\big]^{4 \times 0.1} = \big[(s_5, -0.075), (s_5, -0.075)\big],$$

$$\dot{\tilde{a}}_4 = \big[(s_4, 0), (s_6, 0)\big]^{4 \times 0.4} = \big[(s_2, -0.003), (s_3, 0.023)\big].$$

Similar to Example 2, we have

$$p_1 = 0.962, \qquad p_2 = 2.742, \qquad p_3 = 3.258, \qquad p_4 = 1.038.$$

Then the arguments $\dot{\tilde{a}}_i$ $(i = 1, 2, 3, 4)$ can be ranked in descending order in line with the values of p_i $(i = 1, 2, 3, 4)$:

$$\dot{\tilde{a}}_{\sigma(1)} = \dot{\tilde{a}}_3 = \big[(s_5, -0.075), (s_5, -0.075)\big],$$

$$\dot{\tilde{a}}_{\sigma(2)} = \dot{\tilde{a}}_2 = \big[(s_4, -0.052), (s_5, -0.030)\big],$$

$$\dot{\tilde{a}}_{\sigma(3)} = \dot{\tilde{a}}_4 = \big[(s_2, -0.003), (s_3, 0.023)\big],$$

$$\dot{\tilde{a}}_{\sigma(4)} = \dot{\tilde{a}}_1 = \big[(s_1, 0.072), (s_3, 0.074)\big].$$

Thus,

$$\begin{aligned}
&\text{ITHG}_{\omega, w}(\tilde{a}_1, \tilde{a}_2, \tilde{a}_3, \tilde{a}_4) \\
&\quad = \big[(s_5, -0.075), (s_5, -0.075)\big]^{0.1} \otimes \big[(s_4, -0.052), (s_5, -0.030)\big]^{0.4} \\
&\quad\quad \otimes \big[(s_2, -0.003), (s_3, 0.023)\big]^{0.3} \otimes \big[(s_1, 0.072), (s_3, 0.074)\big]^{0.2} \\
&\quad = \Delta[0.431, 0.615] = [(s_3, -0.069), (s_5, -0.051)].
\end{aligned}$$

5. The Proposed Green Supplier Selection Approach

In this section, we investigate green supplier selection problems based on the proposed interval 2-tuple linguistic hybrid aggregation operators, where the criteria weights take the form of real numbers and criteria values take the form of interval 2-tuple linguistic variables.

Suppose that a green supplier selection problem has l decision makers DM_k $(k = 1, 2, \ldots, l)$, m alternatives A_i $(i = 1, 2, \ldots, m)$, and n evaluation criteria C_j $(j =$

$1, 2, \ldots, n$). Each decision maker DM_k is specified a weight $\lambda_k > 0$ ($k = 1, 2, \ldots, l$) satisfying $\sum_{k=1}^{l} \lambda_k = 1$ to reflect his/her relative prominence in the group green supplier selection process. Let $D_k = (d_{ij}^k)_{m \times n}$ be the linguistic assessment matrix of the kth decision maker, where d_{ij}^k is the linguistic information provided by DM_k on the assessment of A_i with respect to C_j. Let $w = (w_1, w_2, \ldots, w_n)^T$ be the weight vector of evaluation criteria, where $w_j \in [0, 1]$ and $\sum_{j=1}^{n} w_j = 1$. In addition, different linguistic term sets may be adopted by the decision makers to express their assessment values on the performance of green suppliers.

In the following, we apply the developed interval 2-tuple linguistic hybrid aggregation operators to address the green supplier selection problems in the interval 2-tuple linguistic context. The method involves the following steps:

Step 1. Convert the linguistic assessment matrix $D_k = (d_{ij}^k)_{m \times n}$ into an interval 2-tuple linguistic assessment matrix $\tilde{R}_k = (\tilde{r}_{ij}^k)_{m \times n} = ([(s_{ij}^k, 0), (t_{ij}^k, 0)])_{m \times n}$, where $s_{ij}^k, t_{ij}^k \in S$, $S = \{s_0, s_1, \ldots, s_g\}$ and $s_{ij}^k \leqslant t_{ij}^k$.

Suppose that DM_k provides assessments in a set of five linguistic terms and the linguistic term set is denoted as $S = \{s_0 = Very\ poor, s_1 = Poor, s_2 = Medium, s_3 = Good, s_4 = Very\ good\}$. Then, the linguistic information provided in the linguistic assessment matrix D_k can be converted into interval 2-tuple linguistic assessments according to the following ways:

1. A certain rating such as *Poor* can be denoted as $[(s_1, 0), (s_1, 0)]$.
2. An interval grade, e.g. *Poor-Medium*, can be expressed as $[(s_1, 0), (s_2, 0)]$. This means that the rating of an alternative concerning the criterion under consideration is between *Poor* and *Medium*.
3. If a decision maker is not willing to or cannot provide a judgement for an alternative concerning the criterion under consideration, then the assessment could be anywhere between *Very poor* and *Very good* and thus can be written as $[(s_0, 0), (s_4, 0)]$.

Step 2. Utilize the interval 2-tuple linguistic assessment matrix $\tilde{R}_k = (\tilde{r}_{ij}^k)_{m \times n}$ and the ITWA operator to compute the individual overall assessment value $\tilde{r}_i^k$ of alternative A_i corresponding to decision maker DM_k.

$$\tilde{r}_i^k = \left[(s_i^k, \alpha_i^k), (t_i^k, \varepsilon_i^k) \right] = \mathrm{ITWA}_w (\tilde{r}_{i1}^k, \tilde{r}_{i2}^k, \ldots, \tilde{r}_{in}^k),$$
$$i = 1, 2, \ldots, m, \quad k = 1, 2, \ldots, l. \tag{18}$$

Step 3. By using the interval 2-tuple linguistic hybrid aggregation operators, we can get the collective overall assessment values $\tilde{r}_i$ of the alternative A_i:

$$\tilde{r}_i = \left[(s_i, \alpha_i), (t_i, \varepsilon_i) \right] = \mathrm{ITHA}_{\omega, \lambda} (\tilde{r}_i^1, \tilde{r}_i^2, \ldots, \tilde{r}_i^l), \quad i = 1, 2, \ldots, m, \tag{19}$$

or

$$\tilde{r}_i = \left[(s_i, \alpha_i), (t_i, \varepsilon_i) \right] = \mathrm{ITOWAWA}_{\omega, \lambda} (\tilde{r}_i^1, \tilde{r}_i^2, \ldots, \tilde{r}_i^l), \quad i = 1, 2, \ldots, m, \tag{20}$$

or

$$\tilde{r}_i = \big[(s_i, \alpha_i), (t_i, \varepsilon_i)\big] = \text{ITHG}_{\omega, \lambda}\big(\tilde{r}_i^1, \tilde{r}_i^2, \ldots, \tilde{r}_i^l\big), \quad i = 1, 2, \ldots, m, \tag{21}$$

where $\omega = (\omega_1, \omega_2, \ldots, \omega_l)^T$ is the associated weighting vector of the interval 2-tuple linguistic hybrid aggregation operators, such that $\omega_j \geqslant 0$ and $\sum_{j=1}^l \omega_j = 1$.

Step 4. Once the collective overall assessment values $\tilde{r}_i$ $(i = 1, 2, \ldots, m)$ are obtained, we rank them based on the definition of the degree of possibility.

We first compare each $\tilde{r}_i$ with all $\tilde{r}_j$ $(j = 1, 2, \ldots, m)$ by using Eq. (8). Let $p_{ij} = p(\tilde{r}_i \geqslant \tilde{r}_j)$, then a complementary matrix can be derived as $P = (p_{ij})_{m \times m}$, where $p_{ij} \geqslant 0$, $p_{ij} + p_{ji} = 1$, $p_{ii} = 0.5$ $(i, j = 1, 2, \ldots, m)$. By summing all elements in each line of the matrix P, we have $p_i = \sum_{j=1}^m p_{ij}$ $(i = 1, 2, \ldots, m)$. As a result, the values of $\tilde{r}_i$ $(i = 1, 2, \ldots, m)$ can be ordered in descending order based on the values of p_i $(i = 1, 2, \ldots, m)$.

Step 5. Finally, the ranking of all the alternative green suppliers A_i $(i = 1, 2, \ldots, m)$ can be determined and we can select the most desirable one(s) in accordance with $\tilde{r}_i$ $(i = 1, 2, \ldots, m)$.

6. Illustrative Example

In what follows, a practical example is presented to illustrate the developed green supplier selection model. A comparison is also made between the results of the proposed approach and some extant methods to validate the proposed approach.

6.1. *Application of the Proposed Approach*

With the increased awareness of environmental issues worldwide, green SCM has played an important role in marketing economy and has become the hottest research topic in modern enterprise production operation management. Green supplier evaluation and selection are one of the most important problems in green SCM, which directly impact on a manufacturer's environment performance. Suppose that an automobile manufacturing enterprise needs to select the best green supplier for purchasing the key components of its new automobile equipment. After a preliminary screening, five potential automobile equipment suppliers, A_1, A_2, A_3, A_4 and A_5, have been designated for further evaluation. An expert committee of four decision makers, DM_1, DM_2, DM_3 and DM_4, has been formed to conduct the interview and to select the most suitable supplier. The selection decision is made on the basis of one objective and four green criteria C_1, C_2, C_3 and C_4. These criteria, which are critical for the green supplier evaluation process, include Green product innovation (C_1), Use of environmentally friendly technology (C_2), Green competencies (C_3), and Pollution production (C_4). The weight vector of these criteria is $w = (0.23, 0.27, 0.31, 0.19)^T$. Note that the four green criteria are used here for demonstration purposes only. A variety of green criteria have been used in the literature for

evaluating and selecting suppliers, and the most widely considered criteria for green supplier selection have been reviewed and summarized in Govindan *et al.* (2015). Therefore, in actual applications, the green criteria can be selected according to the specific problem considered and the opinions of decision makers.

The four decision makers, whose weight vector is $\lambda = (0.15, 0.2, 0.3, 0.35)^T$, employ different linguistic term sets to evaluate the alternative suppliers with respect to the above evaluation criteria. Specifically, DM_1 provides his assessments in the set of 5 labels, A; DM_2 provides his assessments in the set of 7 labels, B; DM_3 provides his assessments in the set of 9 labels, C; DM_4 provides his assessments in the set of 5 labels, D. These linguistic term sets are denoted as follows:

$$A = \{a_0 = Very\ poor(VP), a_1 = Poor(P), a_2 = Medium(M), a_3 = Good(G),$$
$$a_4 = Very\ good(VG)\},$$
$$B = \{b_0 = Very\ poor(VP), b_1 = Poor(P), b_2 = Medium\ poor(MP),$$
$$b_3 = Medium(M), b_4 = Medium\ good(MG), b_5 = Good(G),$$
$$b_6 = Very\ good(VG)\},$$
$$C = \{c_0 = Extreme\ poor(EP), c_1 = Very\ poor(VP), c_2 = Poor(P),$$
$$c_3 = Medium\ poor(MP), c_4 = Medium(M), c_5 = Medium\ good(MG),$$
$$c_6 = Good(G), c_7 = Very\ good(VG), c_8 = Extreme\ good(EG)\},$$
$$D = \{d_0 = Very\ poor(VP), d_1 = Poor(P), d_2 = Medium(M), d_3 = Good(G),$$
$$d_4 = Very\ good(VG)\}.$$

The linguistic assessments of the five suppliers on each criterion provided by the four decision makers are presented in Table 1, where ignorance information is highlighted and shaded.

In the following, we utilize the proposed decision making approach to derive the most desirable green supplier, which consists of the following steps:

Step 1. Convert the linguistic assessment information shown in Table 1 into the interval 2-tuple linguistic decision matrixes $\tilde{R}_k = ([(s_{ij}^k, 0), (t_{ij}^k, 0)])_{5 \times 4}$ ($k = 1, 2, 3, 4$), which are depicted in Table 2.

Step 2. Based on the ITWA operator and the assessment information given in matrixes $\tilde{R}_k$ ($k = 1, 2, 3, 4$), the individual overall assessment values $\tilde{r}_i^k$ of the five alternatives A_i ($i = 1, 2, \ldots, 5$) are computed as shown in Table 3.

Step 3. The collective overall assessment values $\tilde{r}_i$ of the alternatives A_i ($i = 1, 2, \ldots, 5$) are obtained utilizing the ITHA, the ITOWAWA and the ITHG operators. The results are given in Table 4. In this example, the associated weight vector of the interval 2-tuple linguistic hybrid aggregation operators is $\omega = (0.1117, 0.2365, 0.2365, 0.1117)^T$ (see Xu, 2005 for more details). Note that the parameter ϕ representing the importance of each concept in the ITOWAWA operator is assumed to be 0.5 in this case study.

Table 1
Linguistic assessments of the five alternatives.

Decision makers	Alternatives	Criteria			
		C$_1$	C$_2$	C$_3$	C$_4$
DM$_1$	A$_1$	G	G	G	M-G
	A$_2$	G	M	M-G	G
	A$_3$	M-G	G		M-G
	A$_4$	G	G	M-G	VG
	A$_5$	G-VG	VG	G	G
DM$_2$	A$_1$	VG	M	MG	MG-G
	A$_2$	G	M-MG	MG	M
	A$_3$		G	MG-G	G
	A$_4$	MG	MG	G	G
	A$_5$	G-VG	G	G	VG
DM$_3$	A$_1$	VG	MG	MG-VG	G
	A$_2$	G	M	MG	M-MG
	A$_3$	M-G	G	G	MG
	A$_4$	M		M	G
	A$_5$	G-EG	G	G-VG	G
DM$_4$	A$_1$	G	M	G-VG	G
	A$_2$	M-G	M-G	G	M
	A$_3$	G	VG	G-VG	G
	A$_4$	G	G	G	
	A$_5$	G-VG	VG	VG	G

Table 2
Interval 2-tuple linguistic assessment matrixes of the four decision makers.

Decision makers	Candidates	Criteria			
		C$_1$	C$_2$	C$_3$	C$_4$
DM$_1$	A$_1$	$[(a_3,0),(a_3,0)]$	$[(a_3,0),(a_3,0)]$	$[(a_3,0),(a_3,0)]$	$[(a_2,0),(a_3,0)]$
	A$_2$	$[(a_3,0),(a_3,0)]$	$[(a_2,0),(a_2,0)]$	$[(a_2,0),(a_3,0)]$	$[(a_3,0),(a_3,0)]$
	A$_3$	$[(a_2,0),(a_3,0)]$	$[(a_3,0),(a_3,0)]$	$[(a_0,0),(a_4,0)]$	$[(a_2,0),(a_3,0)]$
	A$_4$	$[(a_3,0),(a_3,0)]$	$[(a_3,0),(a_3,0)]$	$[(a_2,0),(a_3,0)]$	$[(a_4,0),(a_4,0)]$
	A$_5$	$[(a_3,0),(a_4,0)]$	$[(a_4,0),(a_4,0)]$	$[(a_3,0),(a_3,0)]$	$[(a_3,0),(a_3,0)]$
DM$_2$	A$_1$	$[(b_6,0),(b_6,0)]$	$[(b_3,0),(b_3,0)]$	$[(b_4,0),(b_4,0)]$	$[(b_4,0),(b_5,0)]$
	A$_2$	$[(b_5,0),(b_5,0)]$	$[(b_3,0),(b_4,0)]$	$[(b_4,0),(b_4,0)]$	$[(b_3,0),(b_3,0)]$
	A$_3$	$[(b_0,0),(b_6,0)]$	$[(b_5,0),(b_5,0)]$	$[(b_4,0),(b_5,0)]$	$[(b_5,0),(b_5,0)]$
	A$_4$	$[(b_4,0),(b_4,0)]$	$[(b_4,0),(b_4,0)]$	$[(b_5,0),(b_5,0)]$	$[(b_5,0),(b_5,0)]$
	A$_5$	$[(b_5,0),(b_6,0)]$	$[(b_5,0),(b_5,0)]$	$[(b_5,0),(b_5,0)]$	$[(b_6,0),(b_6,0)]$
DM$_3$	A$_1$	$[(c_7,0),(c_7,0)]$	$[(c_5,0),(c_5,0)]$	$[(c_5,0),(c_7,0)]$	$[(c_6,0),(c_6,0)]$
	A$_2$	$[(c_6,0),(c_6,0)]$	$[(c_4,0),(c_4,0)]$	$[(c_5,0),(c_5,0)]$	$[(c_4,0),(c_5,0)]$
	A$_3$	$[(c_4,0),(c_6,0)]$	$[(c_6,0),(c_6,0)]$	$[(c_6,0),(c_6,0)]$	$[(c_5,0),(c_5,0)]$
	A$_4$	$[(c_4,0),(c_4,0)]$	$[(c_0,0),(c_8,0)]$	$[(c_4,0),(c_4,0)]$	$[(c_6,0),(c_6,0)]$
	A$_5$	$[(c_6,0),(c_8,0)]$	$[(c_6,0),(c_6,0)]$	$[(c_6,0),(c_7,0)]$	$[(c_6,0),(c_6,0)]$
DM$_4$	A$_1$	$[(d_3,0),(d_3,0)]$	$[(d_2,0),(d_2,0)]$	$[(d_3,0),(d_4,0)]$	$[(d_3,0),(d_3,0)]$
	A$_2$	$[(d_2,0),(d_3,0)]$	$[(d_2,0),(d_3,0)]$	$[(d_3,0),(d_3,0)]$	$[(d_2,0),(d_2,0)]$
	A$_3$	$[(d_3,0),(d_3,0)]$	$[(d_4,0),(d_4,0)]$	$[(d_3,0),(d_4,0)]$	$[(d_3,0),(d_3,0)]$
	A$_4$	$[(d_3,0),(d_3,0)]$	$[(d_3,0),(d_3,0)]$	$[(d_3,0),(d_3,0)]$	$[(d_0,0),(d_4,0)]$
	A$_5$	$[(d_3,0),(d_4,0)]$	$[(d_4,0),(d_4,0)]$	$[(d_4,0),(d_4,0)]$	$[(d_3,0),(d_3,0)]$

Table 3

Individual overall assessment values of the alternatives.

Alternatives	Decision makers			
	DM_1	DM_2	DM_3	DM_4
A_1	Δ[0.7025, 0.7500]	Δ[0.6983, 0.7300]	Δ[0.7063, 0.7838]	Δ[0.6825, 0.7600]
A_2	Δ[0.6050, 0.6825]	Δ[0.6283, 0.6733]	Δ[0.5963, 0.6200]	Δ[0.5775, 0.7025]
A_3	Δ[0.4125, 0.8275]	Δ[0.5900, 0.8717]	Δ[0.6688, 0.7263]	Δ[0.8175, 0.8950]
A_4	Δ[0.7200, 0.7975]	Δ[0.7500, 0.7500]	Δ[0.4125, 0.6825]	Δ[0.6075, 0.7975]
A_5	Δ[0.8175, 0.8750]	Δ[0.8650, 0.9033]	Δ[0.7500, 0.8463]	Δ[0.8950, 0.9525]

Table 4

Collective overall assessment values of the alternatives.

	Alternatives				
	A_1	A_2	A_3	A_4	A_5
By ITHA	Δ[0.4864, 0.5297]	Δ[0.4190, 0.4589]	Δ[0.4569, 0.5664]	Δ[0.4022, 0.5138]	Δ[0.5713, 0.6187]
By ITOWAWA	Δ[0.5901, 0.6429]	Δ[0.5069, 0.5705]	Δ[0.5509, 0.6999]	Δ[0.5210, 0.6424]	Δ[0.7078, 0.7603]
By ITHG	Δ[0.7788, 0.8262]	Δ[0.7017, 0.7473]	Δ[0.7328, 0.8931]	Δ[0.6976, 0.8222]	Δ[0.8897, 0.9356]

Table 5

The p values and rankings of collective overall assessments.

	$\tilde{r}_1$	$\tilde{r}_2$	$\tilde{r}_3$	$\tilde{r}_4$	$\tilde{r}_5$	Ranking
ITHA	2.799	0.888	2.753	1.560	4.500	$\tilde{r}_5 \succ \tilde{r}_1 \succ \tilde{r}_3 \succ \tilde{r}_4 \succ \tilde{r}_2$
ITOWAWA	2.656	0.860	2.613	1.871	4.500	$\tilde{r}_5 \succ \tilde{r}_1 \succ \tilde{r}_3 \succ \tilde{r}_4 \succ \tilde{r}_2$
ITHG	2.697	0.863	2.682	1.774	4.484	$\tilde{r}_5 \succ \tilde{r}_1 \succ \tilde{r}_3 \succ \tilde{r}_4 \succ \tilde{r}_2$

Table 6

Rankings of the five alternative suppliers.

	Alternatives				
	A_1	A_2	A_3	A_4	A_5
ITHA	2	5	3	4	1
ITOWAWA	2	5	3	4	1
ITHG	2	5	3	4	1

Step 4. The collective overall assessment values are ranked on the basis of the degree of possibility of interval 2-tuple linguistic variables. The p values of the collective overall assessment values are computed first and shown in Table 5. Then we rank $\tilde{r}_i$ ($i = 1, 2, \ldots, 5$) in descending order according to the values of p_i ($i = 1, 2, \ldots, 5$).

Step 5. At last, the five alternatives A_i ($i = 1, 2, \ldots, 5$) are prioritized in accordance with the collective overall assessment values $\tilde{r}_i$ ($i = 1, 2, \ldots, 5$), and the ranking orders are listed in Table 6. Therefore, the most desirable green supplier is A_5.

It may be mentioned that depending on the particular type of aggregation operator used in the proposed green supplier selection method, the results may be different leading to different rankings of the considered suppliers. As a result, the decision maker can select the most suitable green supplier according to their interests and the actual needs. But in this example, it seems clear that A5 is the optimal choice.

Table 7
Ranking results according to the comparative methods.

Alternatives	Fuzzy TOPSIS		COPRAS-G		ITL-VIKOR		The proposed
	CC_i	Ranking	RS_i	Ranking	Q_i	Ranking	method
A_1	0.493	2	0.201	2	0.713	3	2
A_2	0.123	5	0.181	5	0.988	5	5
A_3	0.475	3	0.200	3	0.512	2	3
A_4	0.310	4	0.190	4	0.909	4	4
A_5	1.000	1	0.229	1	0.000	1	1
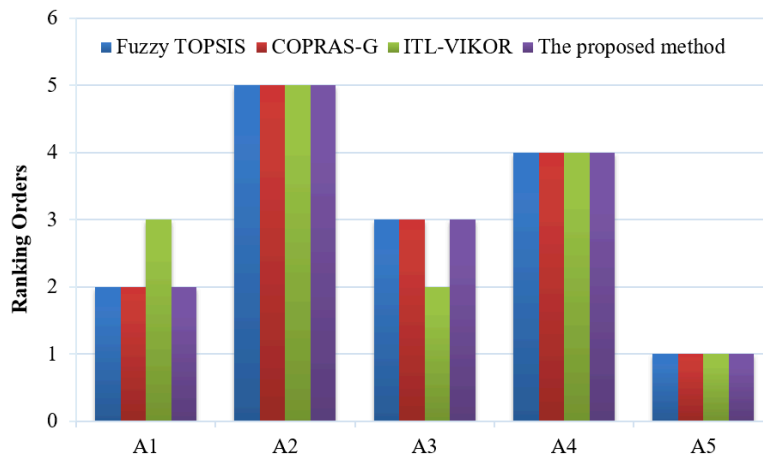
Fig. 1. Rankings of suppliers by the four different methods.

6.2. *Comparative Analysis*

To further validate the proposed approach, we provide a comparative analysis with some
existing green supplier selection methods for the above case study, which include the fuzzy
TOPSIS (Fallahpour *et al.*, 2017a), the COPRAS-G (Liou *et al.*, 2016), and the interval
2-tuple linguistic VIKOR (ITL-VIKOR) (You *et al.*, 2015) methods. The ranking results
of the five alternative suppliers obtained by utilizing these methods are shown in Table 7.
Figure 1 describes the ranking orders as determined by the four methods for the sake of
visual representation.

   From Table 7 and Fig. 1, it can be observed that the best and the last two suppliers
determined by the four methods are identical. Especially, the rankings of the alternative
suppliers obtained using the proposed approach match quite well with those derived by
the fuzzy TOPSIS and the COPRAS-G methods. Therefore, the effectiveness of the pro-
posed approach for practical applications is validated through the comparative analysis.
But different from the previous methods, the proposed green supplier selection approach
has the following advantages: (1) The diversity and uncertainty of decision makers' as-
sessment information can be well represented using interval 2-tuple linguistic variables.
The proposed method can also effectively avoid the loss and distortion of information in

the linguistic information computing. (2) More green criteria can be considered in the green supplier selection if necessary. The proposed approach is a general method and not limited to the four criteria used in the case study, but applicable to any number of green criteria. (3) Based on the developed interval 2-tuple linguistic hybrid aggregation operators, the importance degrees of both the given arguments and their ordered positions can be reflected in the prioritization of green suppliers. Furthermore, complete information for selecting the optimal green supplier can be obtained by taking different types of hybrid aggregation operators into consideration. Therefore, the approach proposed in this paper can generate a more precise and rational ranking result of green suppliers for a specific application. It is very suitable for dealing with the green supplier evaluation and selection problems with interval 2-tuple linguistic information.

7. Conclusions

Green supply chain management is a hot topic in recent years due to the increasing level of pollution and the deterioration of the environment. In this study, we examined the green supplier selection problems in which the criteria values are in the form of interval 2-tuples. First, we introduced some interval 2-tuple linguistic hybrid aggregation operators, such as the ITHA operator, the ITOWAWA operator and the ITHG operator. Furthermore, we applied the developed operators to deal with multiple criteria green supplier selection problems under the interval 2-tuple linguistic environment. Finally, a practical example in the automobile manufacturing industry has been given to verify the developed green supplier selection approach and to demonstrate its benefits and effectiveness. The results show that the proposed method is straightforward and has no loss of information; the decision makers can naturally provide their assessments by using the interval 2-tuple linguistic approach under multi-granular linguistic context.

In the future, we expect to develop further extensions to the proposed green supplier selection approach by adding new characteristics in the decision process, such as the use of dependent aggregation operators (Liu *et al.*, 2014), order inducing variables (Merigó, 2011), decision field theory (Hao *et al.*, 2017), and alternative queuing method (Gou *et al.*, 2016). In future research, it is also interesting to apply the developed interval 2-tuple linguistic aggregation operators to other domains.

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