An Integrated Multicriteria Group Decision-Making Approach for Green Supplier Selection Under Pythagorean Fuzzy Scenarios

FANG ZHOU1,2 AND TING-YU CHEN1,3,4

1Graduate Institute of Business and Management, Chang Gung University, Taoyuan 33302, Taiwan
2Department of Economic and Management, Suzhou Vocational Institute of Industrial Technology, Suzhou 215000, China
3Department of Industrial and Business Management, Chang Gung University, Taoyuan 33302, Taiwan
4Department of Nursing, Linkou Chang Gung Memorial Hospital, Taoyuan 33305, Taiwan

Corresponding author: Ting-Yu Chen (tychen@mail.cgu.edu.tw)

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ABSTRACT As a critical component in green supply chain activities, green supplier selection modelled as the typical multicriteria group decision-making (MCGDM) problem, has received tremendous attention both from scholars and practitioners. This article aims to advance an integrated approach for precisely addressing this urgent problem under Pythagorean fuzzy (PF) scenario. Firstly, analytic hierarchy process (AHP) is utilized for computing criterion weights that comprehensively reflect the intention of decision makers (DMs). Secondly, extend the Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) to PF scenario, and apply the newest magnitude comparison method and distance measure of PF sets in the \( L_p \) metric equation to accurately acquire the ranking indices, then obtain the different ranks of candidates along with the adjustment of DM’s preference value to balance the group utility and individual regret. Thirdly, median ranking method (MRM) is employed to reach a consensus opinion for the differentiated ranks of candidates via the attribute-wise rank and linear programming model. Subsequently, a numerical example for an agri-food company in China is introduced to illustrate the feasibility of our AHP-VIKOR-MRM method. Finally, conduct the comparison with some available MCGDM methods with PF information to interpret the stability and practicability of our presented method.

INDEX TERMS Vise kriterijumska optimizacija i kompromisno resenje (VIKOR), analytic hierarchy process (AHP), median ranking method (MRM), Pythagorean fuzzy (PF) sets, green supplier.

I. INTRODUCTION

As the prosperity and booming economy, environmental issues are widely concerned by the government, society, and the consumers. The government has developed the tightened environmental regulation, and the consumers have been aware of necessity of the green products [1]. Therefore, green supply chain plays a major role in micro enterprises’ production operation management [2]. It is required that the organizations should not only take measures to green the intra-organizational performance manipulation, such as green manufacturing production, storage, packaging, and logistics, but also carry out the green inter-organizational performance [3]. Green supplier selection is a crucial operational task to choose the green partnership via supplier evaluation considering both economic factors and environmental factors, such as energy utilization, carbon footprint, water usage and recycling engagement, which are of vital importance for building eco-efficient supply chain [4].

Selecting an appropriate green supplier involves conflicting criteria and several decision makers (DMs), and is modelled as a representative of multicriteria group decision making (MCGDM) problem. Since awareness of importance of green supplier chain, numerous scholars and practitioners have drawn extensively attention to design evaluation criteria, optimize evaluation model, and apply various MCGDM methods to address this problem, including analytic hierarchy process (AHP) [5], technique for order preference
by similarity to ideal solutions (TOPSIS) [6], Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [7], Elimination and choice Expressing Reality (ELECTRE) [8], qualitative flexible multiple-criteria method (QUAFLLEX) [9], preference ranking organization method for enrichment evaluation (PROMATHEE) [10], grey relational analysis (GRA) [11], etc. Among available MCGDM methods, VIKOR has some unique characteristics and advantages compared to other MCGDM techniques: (1) VIKOR is superior in handling problems with incompatible or contradictory criteria; (2) VIKOR is deemed as a renowned tool to trade off the group utility and individual regret based on DM’s subjective preference; (3) VIKOR provides optimal solution or ranks of alternatives via the acceptable advantage and stability test [7, 12]–[14]. Therefore, VIKOR is considered as the first choice to choose the optimal green supplier. Besides, AHP is deemed as an effective tool to identify the criterion weights because of its relative ease to comprehend and dispose of qualitative or quantitative information [15]–[17].

Due to the restricted cognition and experience of DMs in real-life practice, the crisp number may not clearly express their judgments regarding the green supplier’s performance [18]. Zadhah [19] pioneered the fuzzy set doctrine by membership to express the imprecise and vague information, and the trapezoidal fuzzy (TRAF) set and triangular fuzzy (TRIF) set are the most popular fuzzy forms. Atanassov [20] presented the intuitionistic fuzzy (IF) set with nonmembership to further reflect the uncertainties of opposition fulfilling the condition that summation of degrees of membership and nonmembership is no greater than one. Yager [21] initiated the Pythagorean fuzzy (PF) set meeting the condition that summation of both degrees is no greater than one, which has greater space to reflect the vague information compared to IF set. Therefore, PF set has greater power to describe the ambiguous information in MCGDM practice. Recently, many researches have applied the VIKOR to choose the appropriate green supplier under fuzzy scenarios [15], [22]–[26]. However, we haven’t found any single VIKOR or hybrid VIKOR methods are extended to PF scenario for choosing the green suppliers. Hence, it is urgent and worthwhile to extend VIKOR to PF scenario to effectively reflect the uncertain judgments, and assist DMs in precisely addressing this MCGDM problem.

Obviously, some difficulties need to be resolved when we apply the VIKOR for group green supplier selection problem in PF scenario: (1) A set of hierarchical criteria should be established, and the corresponding criterion weights should be identified; (2) The latest PF concepts should be applied in the process of VIKOR, such as fundamental operators, magnitude comparison, and distance measure; (3) The different DMs’ preference values that balance the group utility and individual regret should be considered in the group decision making, then the obtained ranking orders should be reached a consensus opinion. Therefore, this article aims to integrate the AHP, VIKOR, and MRM (median ranking method) [27] with PF information to resolve the afore-mentioned difficulties one by one, then efficiently address this MCGDM problem.

The remaining sections are outlined as below: Section II systematically recalls the criteria and methods to evaluate the green suppliers, then presents the primary study and contributions. Section III briefly reviews some fundamental concepts, operations, distance measurement methods, and magnitude laws of the PF sets. Section IV integrates the AHP, VIKOR, and MRM methods for the MCGDM problems under PF scenario. Section V takes an agri-food corporation choosing the green supplier for numerical case to interpret our method, then perform the comparison with available PF-MCGDM methods to show the core advantages of our hybrid method. Finally, some managerial implications along with future prospect are put forward in Section VI.

II. LITERATURE REVIEW

This section roughly recalls the criteria and techniques to choose an optimal green supplier, summarizes some drawbacks in available single and hybrid fuzzy VIKOR methods, then outlines the primary study and contributions of this article.

A. CRITERIA FOR GREEN SUPPLIER EVALUATION

As a vital component in eco-supply chain, green supplier evaluation has attracted abundant studies to develop the evaluation model that includes diversity criteria. Through literature review in last decade, the derived criteria are composed by traditional and environmental factors [28]. Traditional criteria are mainly expressed as economic factors: quality, service, and price [25], [29]–[31]. The environmental sustainability taken into supplier selection process is possibly initiated by Noci [32], then some scholars explored the environment factors, among which environmental management system (EMS) is a popular and comprehensive indicator [28], [33], [34]. EMS is regarded as a succession of practices that realize environmental protection, improve energy saving, and reduce emission, including environmental policy, environmental planning, environment operation measures [33], codes of conducts and standards like ISO 14000, REACH, RoHS and WEEE [25], [35]–[37]. Moreover, Grisi et al. [38], Darabi and Heydari [39], and Wan et al. [34] pointed out the environmental competence is an important indicator to evaluate the green suppliers, which defines the capability to reduce the environmental pressures in the production, such as ecological materials, clean technologies, etc. Wan et al. [40] defined energy consumption, resource recycling, environmental impact, energy identification, and environmental defense funds as criteria to assess the green suppliers.

However, two limitations are discovered in the existing criteria for choosing the green supplier: (1) Extant criteria simply combined the environmental factors and traditional factors, but both haven’t achieved penetration. (2) Quality, service, price/cost, and EMS can be deemed as the main criteria, but it is urgent to build the corresponding subcriteria to precisely measure the performance of the green suppliers.
From this perspective, this paper intends to construct a hierarchical criteria system based on previous relevant bibliography, namely, quality, service, price/cost, and EMS are designed as the main criteria, which are further specified into subcriteria that are penetrated environmental factors. It is worth mentioning, environmental competence is placed in quality, expressed as green material, green product, green production, etc. A hierarchical criteria system and corresponding definitions are displayed in Table 1, which are applied in the following evaluation practice.

| Category         | Criteria                                                                 | Definitions                                                                 | Citations |
|------------------|--------------------------------------------------------------------------|----------------------------------------------------------------------------|-----------|
| Green material   | Materials coexist in harmony with ecological environment, and are conducive to human health. |                                                                              | [34], [36], [37], [39], [44] |
| Green product    | It is a notarized appraisal of environmental performance of products.    | The continuous application of environmental protection strategies in the process of production. |           |
| Quality          |                                                                           | Choosing scientific routes, vehicles, assembling to reduce exhaust emissions, resource consumption, etc. |           |
| Green production |                                                                           | The appearance of the site, physical equipment and service personnel.        |           |
| Green delivery   |                                                                           |                                                                           |           |
| Tangible         |                                                                           |                                                                           |           |
| Reliability      |                                                                           |                                                                           |           |
| Service          |                                                                           |                                                                           |           |
| Responsiveness   |                                                                           |                                                                           |           |
| Assurance        |                                                                           |                                                                           |           |
| Product price    |                                                                           |                                                                           |           |
| Price/ Cost      |                                                                           |                                                                           |           |
| Service price    |                                                                           |                                                                           |           |
| Capital and financial power | The financial performance shows the ability to acquire resource, provide the environmental protection. | [33], [46], [48] |
| Environment commitment | The promise of improving the quality of the sustainable environment. | [33], [34], [36], [37], [40], [46] |
| EMS              |                                                                           |                                                                           |           |

**B. FUZZY METHODS FOR GREEN SUPPLIER EVALUATION**

As a hot topic within eco-supply chain field under the context of sustainable economic development, a great number of scholars have explored various fuzzy MCGDM methods to assess the performances of green suppliers, which are separated into three models: scoring model, compromising model, and outranking model. Weighted sum model (WSM), weighted product model (WPM), and AHP are typical scoring models via computing the score over the criteria and alternatives. TOPSIS, VIKOR, LINMAP, and TODIM are typical compromising models via comparing with the reference point. ELECTRE, QUALIFLEX, and PROMATHEE are typical outranking models via concordance and discordance comparison between alternatives on the criteria. The latest studies regarding fuzzy-MCGDM methods for selecting green supplier are displayed in Table 2.

As seen in Table 2, VIKOR is one of the most popular methods applied to rank the green suppliers. Since VIKOR can effectively deal with conflicting and incompatible criteria, and consider the subjective preferences of DMs to tradeoff the group utility maximization and individual regret minimization [7], [64], some extensions of traditional VIKOR are developed focusing on fuzzy form, determination of positive ideal solution (PIS) and negative ideal solution (NIS), separation measure, and weight calculation technique.

A summary of basic characteristics regarding single and hybrid fuzzy VIKOR methods to choose the optimal green supplier are displayed in Table 3.

As summarized in Table 3, we discovered some limitations in available related fuzzy-VIKOR methods for the green supplier selection problem, then put forward our motivations of this paper.

First, available VIKOR methods haven’t utilized the PF information to evaluate the green supplier. Though scholars extended the VIKOR method with fuzzy information, such as TRAF sets [22], [23], TRIF sets [15], [25], [65], [66], and IF sets [53], the PF sets haven’t been found in any single or hybrid VIKOR methods for this problem. Owing to the ambiguousness of DM’s cognition and experience, PF sets are superior to traditional fuzzy sets, and have greater power to give prominence for vague information in MCGDM practice.

In this respect, the first motivation of this article is to expand the VIKOR to PF scenario. As the development of the PF theory, the latest researches regarding the fundamental operators, distance measures, and the magnitude comparison laws have gradually improved to embody the charming...
TABLE 3. Summary of fuzzy VIKOR for green supplier selection problem.

| Method        | Fuzzy form | Criteria weight | PIS or NIS | Separation measure | Application | Cit. |
|---------------|------------|-----------------|------------|--------------------|-------------|------|
| VIKOR (Group) | TRAF       | Linguistic variables | Union or intersection | Euclidean distance | Automobile firm | [22] |
| VIKOR (Group) | TRIF       | Linguistic variables | Center of area way | Euclidean distance | Reverse logistics | [23] |
| VIKOR (Group) | IF         | Linguistic variables, entropy | Score and accuracy measure | Distance | Manufacturing firm | [24] |
| FCM-AHP-VIKOR | Fuzzy AHP  | Max and min value | Subtraction of values | Euclidean distance | Automobile manufacturing system | [53] |
| NGT-VIKOR     | TRIF       | Linguistic variables | Max and min value | Subtraction of values | Automobile manufacturing firm | [62] |
| TOPSIS_VIKOR | TRIF       | Linguistic variable | Max/Min of weighted score | Euclidean distance | Agri-food industry | [65] |
| AHP-VIKOR (Group) | TRIF | AHP | Max and min value | Subtraction of values | Electronic manufacturing firm | [25] |
| TOPSIS-VIKOR | TRIF       | Linguistic variable | Max and min value | Euclidean distance | Manufacturing | [15] |

Abbreviations: fuzzy c means (FCM); Nominal Group Technique (NGT); Citation (Cit.)

properties of the PF sets. Therefore, these recent PF theoretical results will be applied in the VIKOR method to effectively address the group green supplier selection problem.

Second, the weight calculation in most fuzzy-VIKOR methods for this problem is directly obtained in view of the linguistic variables, merely Akman [62], and Awasthi et al. [15] identified the criterion weights via AHP, and Zhao et al. [53] determined the criterion weights by entropy.

As an important theme in MCGDM method, how to acquire the feasible and optimal weights has made great progress in view of nature of problem and intention of the DMs. We can roughly classify them into objective weights and subjective weights. As for objective weights, Shannon entropy measure [14], linear programming model [40], [55], [67] are the most used methods. However, some limitations are discovered in the objective weights, namely, the weights are just obtained from the evaluation data, which couldn’t reflect the DMs’ intentions and preferences. As for subjective criteria, AHP is demonstrated as an effective technique to identify the weights via pairwise comparison, and widely used to determine the criterion weights, the results of which are comprehensively influenced by the DMs’ intention, and overcome the defect from method directly obtained from the linguistic variables. Due to the importance of the green supplier in eco-chain system, the DM’s intention plays a decisive role, which may control the initiative of the whole decision making.

From this perspective, the second motivation of this article is to employ the AHP method to determine the evaluation criterion weights at all levels, which may adequately reflect the preference and intention over the importance of the criteria, then effectively address the green supplier selection problem.

Third, some fuzzy-VIKOR methods haven’t reflected the basic sequencing strategy of the VIKOR. Datta et al. [22], Vahazadeh [23], Zhao et al. [53], and Banaeian et al. [15] haven’t tested the “acceptable stability” and “acceptable advantage”, then ranked the green suppliers merely based on the overall values, get the optimal solution from the least overall value, but ignored the consistency with the indices of group utility and individual regret.

From this perspective, the third motivation of this article is to strictly carry out the fundamental procedure of the VIKOR method: determine the PFPIS and PFNIS according to relative distance and information reliability-based method [68], calculate the separation to the PFPIS and PFNIS via the novel distance measure between PF sets that reflects both length distance and angular distance [69], rank the suppliers in accordance with the consistency of the overall value, group utility, and individual regret, and test acceptable stability and advantage. The, the final solution for green supplier selection can be effectively addressed.

Fourth, most available fuzzy-VIKOR methods for group green supplier selection [15], [22], [24], [25], [53] haven’t considered different DM’s preference for the tradeoff between group utility and individual regret. Since the ratings over the criteria are aggregated before using the \( L_p \)-metric equation, the subsequent overall value may result in the loss of the individual DM’s preference. Moreover, how to get a consensus opinion of the providers’ rank should be resolved.

From this perspective, the fourth motivation is to obtain the different alternative ranks along with adjustment of preference values, then acquire the consensus opinion to assist the decision making. MRM is an effective consensus technique for ordinal ranking problems via distance function to measure the agreement and disagreement between rankings [27], [70], [71]. The fundamental strategy of MRM is to obtain the overall ranking differs as little as possible from all available attribute-wise ranks, then arrive at a consensus opinion. Besides, the weights of ranks from different preference values should be obtained, and used in the MRM. The ordered weighted averaging (OWA) within normal distribution deemed as a useful approach to empower the weights since it can decrease affect from biased or false judgements [72]. Therefore, the OWA operator is fit for participating in the MRM to efficaciously reach the consensus optimal solution.

C PRIMARY STUDY AND CONTRIBUTIONS OF THIS PAPER

To overcome the afore-mentioned drawbacks, this article aims to develop a hybrid method that integrates the AHP, VIKOR, and MRM to address the group green supplier selection problem under PF scenario.
Firstly, we construct a set of hierarchical evaluation criteria in allusion to green supplier selection that can fully reflect the green performance of the suppliers, and utilize the AHP to determine the criterion weights that comprehensively reflect the intention of the DMs. Secondly, we extend the VIKOR to PF scenario, obtain the ratings of candidates regarding the differentiated alternatives’ rank based on different preference values, respectively.

Precisely obtain the ranks of the alternatives based on corresponding preference values, the weights of which are identified by OWA within normal distribution [72]. Then, the obtained consensus rank can assist DMs in selecting an appropriate green supplier.

Four major contributions of this article regarding the available fuzzy-VIKOR methods for choosing the green supplier are generalized as below:

1. A set of hierarchical evaluation criteria choosing the green supplier is constructed through systematical review, then the criterion weights are calculated by AHP method via a panel of DMs to fully reflect their intentions for the problem.

2. PF information is applied in VIKOR for selecting the appropriate green supplier. The latest magnitude comparison method and distance measurement approach are applied in the \( L_p \)-metric equation to accurately acquire the ranking indices, and obtain the effective solution for decision making.

3. Different preference values reflecting the subjective judgments from DMs to tradeoff the average gap and maximal gap are taken into consideration. Then, the test of acceptable stability and advantage are strictly performed to precisely obtain the ranks of the alternatives based on corresponding preference values, respectively.

4. The MRM are used to achieve at the consensus opinion of the differentiated alternatives’ rank based on different preference values, the weights of which are computed through OWA within normal distribution. The consensus rank for the group green supplier selection problem is more appropriate and practicable.

### III. CONCEPTS OF PF SETS

This section reviews some fundamental notions, operations, distance measures, and magnitude comparison laws of the PF sets.

#### A. FUNDAMENTAL CONCEPTS OF PF SETS

**Definition 1** [73]: Given a finite universe of discourse \( \Psi \), the PF set \( \beta \) in \( \Psi \) is described via the following from:

\[
\beta = \{ \xi \in \Psi : \mu_\beta (\xi) , v_\beta (\xi) \} | \xi \in \Psi > 0 \},
\]

where \( \mu_\beta (\xi) \) is called membership function that means the degree of belonging to set \( \beta \) in \( \Psi \) with the condition: \( \mu_\beta (\xi) \in [0, 1] \), and \( v_\beta (\xi) \) is called nonmembership function that means the degree of not belonging to set \( \beta \) in \( \Psi \) with the condition: \( v_\beta (\xi) \in [0, 1] \). Given each element \( \xi \) in PF set \( \beta \) and \( \xi \in \Psi \), the following equation fulfills:

\[
0 \leq (\mu_\beta (\xi))^2 + (v_\beta (\xi))^2 \leq 1.
\]

\( h_\beta (\xi) \) is called hesitation function that means the lack of information regarding whether \( \xi \) belongs to \( \beta \) in \( \Psi \). For any element \( \xi \) in PF set \( \beta \) and \( \xi \in \Psi \), the following equation fulfills:

\[
h_\beta (\xi) = \sqrt{1 - (\mu_\beta (\xi))^2 - (v_\beta (\xi))^2}.
\]

For simplicity, Zhang and Xu [73] defined \( P(\mu_\beta (\xi), v_\beta (\xi)) \) as \( P(\mu_\beta, v_\beta) \), called Pythagorean fuzzy number (PFN), and meeting conditions that \( \mu_\beta, v_\beta \in [0, 1] \), \( 0 \leq (\mu_\beta)^2 + (v_\beta)^2 \leq 1 \), and \( h_\beta = (1 - (\mu_\beta)^2 - (v_\beta)^2)^{1/2} \).

Moreover, Yager [21], [74] presented another expression of the PFN: \( \beta = P(\lambda_\beta, d_\beta) \), where \( \lambda_\beta \) is described as the strength of commitment, \( \lambda_\beta = ((\mu_\beta)^2 + (v_\beta)^2)^{1/2} \), and \( \beta_\in [0, 1] \), and \( d_\beta \) is described as the direction of commitment, \( d_\beta = 1 - (2/\pi)\theta_\beta \), where \( \theta_\beta \) is the angle of the PFN, and \( \theta_\beta \in [0, \pi/2] \).

**Definition 2** [21]: Given three PFNs expressed as \( \beta_1 = P(\mu_{\beta_1}, v_{\beta_1}), \beta_2 = P(\mu_{\beta_2}, v_{\beta_2}) \), and \( \beta = P(\mu_\beta, v_\beta) \), their fundamental operators regarding PFNs are described as below:

1. \( \beta_1 \cup \beta_2 = P(\min(\mu_{\beta_1}, \mu_{\beta_2}), \min(v_{\beta_1}, v_{\beta_2})) \).
2. \( \beta_1 \cap \beta_2 = P(\max(\mu_{\beta_1}, \mu_{\beta_2}), \max(v_{\beta_1}, v_{\beta_2})) \).
3. \( \beta^c = P(v_\beta, \mu_\beta) \).

Zhang and Xu [73] further defined some operations of PFNs referring to the IF numbers as follows:

1. \( \beta_1 \oplus \beta_2 = P((\mu_{\beta_1} + \mu_{\beta_2} - \mu_{\beta_1}^2 \mu_{\beta_2}^{1/2})/v_{\beta_1} v_{\beta_2}) \).
2. \( \gamma_\beta = P((1 - (1 - \mu_{\beta_1}^2)^{1/2})^{1/2}, (v_{\beta_1}^2)^{1/2}, \gamma > 0) \).
3. \( \gamma(\beta_1 + \beta_2) = \gamma \beta_1 + \gamma \beta_2, \gamma > 0 \).

PF aggregation operator is used to collect the PFNs for group decision making, which has drawn great attention from scholars. Various PF aggregation operators are emerged, Ma and Xu [75] presented the PF weighted averaging (PFWA) operator and PF weighted geometric operator considering neutral membership degree and non-membership degree; Garg [76] presented the PF generalized averaging aggregation operator; Zeng et al. [77] presented the PF induced OWA weighed average operator; Wei [78] presented the PF interaction aggregation operators considering the interaction between the membership function and non-membership function; and Wang and Li [79] further presented PF interaction power Bonferroni mean aggregation operators. Among available aggregation operators, the PFWA operator is the most widely used in the MCGDM problems.

**Definition 3** [75]: Given a group of PFNs described as \( \beta_j = P(\mu_{\beta_j}, v_{\beta_j}) \), the weight vector of \( \beta_j \) expressed as \( w_j = (w_{j1}, w_{j2}, \ldots, w_{jn})^T \) fulfilling the conditions: \( 0 \leq w_j \leq 1 \) and \( \sum_{j=1}^{n} w_j = 1 \). The PFWA operator can be defined as follows:

\[
PFWA_w(\beta_1, \beta_2, \ldots, \beta_n) = w_1 \beta_1 \oplus w_2 \beta_2 \oplus \ldots \oplus w_n \beta_n
\]
B. DISTANCE MEASURES FOR PFNS

Distance measure for PFNs is also a primary subject, and is fascinated some scholars to present the distance measurement formulas. Zhang and Xu [73] extended Hamming distance measure for IF numbers to PFNs. Then, Li and Zeng [80], Zeng et al. [81] presented the novel distance measures adding parameters λ and d to the formulas. Afterwards, Zhou and Chen [69] identified some defects in available distance measures, and presented a new Hamming distance measure that considered both length distance and angular distance to comprehensively reflect greater spectrum of PFNs, and fulfill unique characteristics of distance measure that have been demonstrated.

**Definition 4 [69]:** Given any two PFNs \( \beta_1 = P(\mu_{\beta_1}, v_{\beta_1}) \) and \( \beta_2 = P(\mu_{\beta_2}, v_{\beta_2}) \), the Hamming distance between \( \beta_1 \) and \( \beta_2 \) can be described as below:

\[
D(\beta_1, \beta_2) = \frac{1}{4} \left( \left| \mu_{\beta_1} - \mu_{\beta_2} \right|^2 + \left| v_{\beta_1} - v_{\beta_2} \right|^2 
+ \left| \lambda_{\beta_1} - \lambda_{\beta_2} \right|^2 + \left| d_{\beta_1} - d_{\beta_2} \right|^2 
+ \left| \sin(\theta_{\beta_1}) - \sin(\theta_{\beta_2}) \right| \right). \tag{5}
\]

**Definition 5 [69]:** Given any two collections of PFNs \( \beta_1 = P(\mu_{\beta_1}, v_{\beta_1}) \) and \( \beta_2 = P(\mu_{\beta_2}, v_{\beta_2}) \) with a serial of criteria, the corresponding weights are described as \( w = (w_1, w_2, \ldots, w_n)^T \), the weighted Hamming distance between \( \beta_1 \) and \( \beta_2 \) can be described as below:

\[
D_w(\beta_1, \beta_2) = \sum_{j=1}^{n} w_j \left( \left| \mu_{\beta_1} - \mu_{\beta_2} \right|^2 + \left| v_{\beta_1} - v_{\beta_2} \right|^2 
+ \left| \lambda_{\beta_1} - \lambda_{\beta_2} \right|^2 + \left| d_{\beta_1} - d_{\beta_2} \right|^2 
+ \left| \sin(\theta_{\beta_1}) - \sin(\theta_{\beta_2}) \right| \right). \tag{6}
\]

C. MAGNITUDE COMPARISON METHODS FOR PFNS

As an important theme, the magnitude comparison method of PFNs has aroused great interest of scholars, and emerged numerous comparison methods, which are classified into the following forms: order-relation-based method [74], scalar function-based method [74], score and accuracy function-based method [73], [82], [83], closeness-based method [84], ratio-based method [85], and distance and information reliability-based method [68].

Wan et al. [68] pointed out the defects of extant magnitude comparison methods, and developed the relative distance and information reliability-based method considering the distances from positive point and negative point, concurrently.

**Definition 6 [68]:** Given any PFN described as \( \beta = P(\mu_{\beta}, v_{\beta}) \), the relative distance of \( \beta \) is described as below:

\[
\mathbb{R}(\beta) = \frac{D(\beta, P^-) + 1}{D(\beta, P^+) + 1}, \tag{7}
\]

where \( D(\beta, P^-) \) defines the distance between \( \beta \) and the negative point \( P^- = P(0, 1) \), and \( D(\beta, P^+) \) defines the distance between \( \beta \) and the positive point \( P^+ = P(1, 0) \). From \( D(\beta, P^-) \) and \( D(\beta, P^+) \in [0, 1] \), it follows that \( \mathbb{R}(\beta) \in [0.5, 2] \).

**Definition 7 [68]:** Given a PFN described as \( \beta = P(\mu_{\beta}, v_{\beta}) \), the information reliability of \( \beta \) is described as below:

\[
I(\beta) = 1 - \left( \frac{\mu_{\beta}v_{\beta} + \frac{1}{2} \arccos \left( \frac{\mu_{\beta}\sqrt{1-(v_{\beta})^2} + v_{\beta}\sqrt{1-(\mu_{\beta})^2}}{\mu_{\beta}\sqrt{1-(\mu_{\beta})^2} + v_{\beta}\sqrt{1-(\mu_{\beta})^2}} \right)}{\frac{1}{2} \left( \mu_{\beta}\sqrt{1-(\mu_{\beta})^2} + v_{\beta}\sqrt{1-(\mu_{\beta})^2} \right)} \right). \tag{8}
\]

**Definition 8 [68]:** For any two PFNs \( \beta_1 = P(\mu_{\beta_1}, v_{\beta_1}) \) and \( \beta_2 = P(\mu_{\beta_2}, v_{\beta_2}) \), the magnitude comparison between \( \beta_1 \) and \( \beta_2 \) abides by the following principles:

(i) If \( \mathbb{R}(\beta_1) > \mathbb{R}(\beta_2) \), then \( \beta_1 > \beta_2 \);
(ii) If \( \mathbb{R}(\beta_1) < \mathbb{R}(\beta_2) \), then \( \beta_1 < \beta_2 \);
(iii) If \( \mathbb{R}(\beta_1) = \mathbb{R}(\beta_2) \), and \( I(\beta_1) > I(\beta_2) \), then \( \beta_1 > \beta_2 \);
If \( \mathbb{R}(\beta_1) = \mathbb{R}(\beta_2) \), and \( I(\beta_1) < I(\beta_2) \), then \( \beta_1 < \beta_2 \);
If \( \mathbb{R}(\beta_1) = \mathbb{R}(\beta_2) \), and \( I(\beta_1) = I(\beta_2) \), then \( \beta_1 = \beta_2 \).

IV. PROPOSED AHP-VIKOR-MRM APPROACH UNDER PF SCENARIO

In this section, a new method integrating the AHP, VIKOR, and MRM under PF scenario for choosing the green supplier is introduced. The AHP is employed to compute the criterion weights via pairwise comparison on the criteria that reflect DMs’ intention and preference. An extended PF-VIKOR that applies the relative distance and information reliability-based magnitude method, latest distance measure for PFNs in the \( L_p \)-metric equation to precisely obtain the ranks of candidates along with different DMs’ preferences. Then, the MRM is utilized to synthesize the different ranks via the attribute-wise rank and linear programming model, then reaches a consensus opinion to get the best choice for the MCGDM problem. The flowchart of our integrated MCGDM method is delineated in Fig.1.

A. DESCRIPTION OF THE MCGDM PROBLEM

Given an MCGDM problem with PF information, let \( A = \{ A_1, A_2, \ldots, A_m \} \) (\( m \geq 2 \)) be the candidates, \( C = \{ C_1, C_2, \ldots, C_n \} \) (\( n \geq 2 \)) be the evaluation criteria determined via a panel of DMs \( E = \{ E_1, E_2, \ldots, E_t \} \) (\( t \geq 2 \)), the weights of which are described as \( \sigma = (\sigma_1, \sigma_2, \ldots, \sigma_t)^T \) satisfying \( 0 \leq \sigma_k \leq 1 \), and \( \sum_{k=1}^{t} \sigma_k = 1 \). Meanwhile, the weights of evaluation criteria are described as \( w = (w_1, w_2, \ldots, w_n)^T \) fulfilling the conditions: \( 0 \leq w_j \leq 1 \), and \( \sum_{j=1}^{n} w_j = 1 \). \( P(\mu_{\beta_j}, v_{\beta_j}) \) describes the evaluation rating of \( i \)-th candidates on \( j \)-th criterion from \( k \)-th DM, namely, \( C_j(\beta_{j}) = P(\mu_{\beta_j}, v_{\beta_j}) \), and \( M^k = (C_j(\beta_j))_{m \times n} \) represents a PF decision.
B. PROCESS OF THE INTEGRATED METHOD

Step 1: Identify the DM’s importance from a serial of linguistic terms expressed by PFNs [86], displayed in Fig. 2. For a PFN $\beta_k = P(\mu_k, v_k)$ it describes the importance of the $k$th DM that can be identified via the following formula:

$$\sigma_k = \frac{(\mu_k + h_k (\mu_k / (\mu_k + v_k)))}{t \sum_{k=1}^{n} (\mu_k + h_k (\mu_k / (\mu_k + v_k)))},$$ (10)

where $h_k = \sqrt{1 - (\mu_k)^2 - (v_k)^2}$.

Step 2: Choose evaluation criteria to handle MCGDM problem. According to available literature regarding criteria for addressing the MCGDM problem, a comprehensive criteria structure including the general objective, first-level criteria, and second-level criteria, are built.

Step 3: Utilize AHP to get the criterion weights. First, considerations from DMs are collected by a questionnaire (nine level pairwise comparison scale) [5], then formulated into a positive reciprocal matrix of pairwise comparison between the criteria.

Let $C = \{C_1, C_2, \ldots, C_n\}$ denote the criteria for the problem, the quantified judgments concerning pairs of criteria ($C_\phi, C_\varphi$) are expressed as an $n$-by-$n$ matrix $B = [b_{\phi\varphi}]$.

$$B = \begin{bmatrix} P(\mu_{11}, v_{11}) & \cdots & P(\mu_{1n}, v_{1n}) \\ P(\mu_{21}, v_{21}) & \cdots & P(\mu_{2n}, v_{2n}) \\ \vdots & \vdots & \vdots \\ P(\mu_{n1}, v_{n1}) & \cdots & P(\mu_{nn}, v_{nn}) \end{bmatrix}$$ (9)

Second, calculate the maximum eigenvector values $\lambda_{\text{max}}$ of $B$, satisfying the equation as follows:

$$Bw = \lambda_{\text{max}}w.$$ (12)

Third, compute the criterion weights from $k$th DM $w_j^k$ ($j = 1, 2, \ldots, n$, and $\sum_{j=1}^{n} w_j^k = 1$), then measure the inconsistency of the pairwise comparison matrix through following consistency index (CI) formula:

$$CI = (\lambda_{\text{max}} - n)/(n - 1).$$ (13)

Fourth, employ the following formula to compute the consistency ratio (CR):

$$CR = CI / RI,$$ (14)

where $RI$ is the reference of the $CI$ of a randomly emerging reciprocal matrix based on 9-level scale. If $CR \leq 0.10$, then $CR$ is considered acceptable.

Fifth, utilize the weighted geometric mean to improve the consistency of the multiplicative preference matrix $B$ when $CR > 0.10$. The weighted geometric mean is computed by the following formula:

$$b_{\phi\varphi}^\delta = b_{\phi\varphi} (w_\phi/w_\varphi)^{1-\delta},$$ (15)

where $\delta \in [0, 1]$, and $\phi, \varphi \in n$.

Sixth, calculate the overall importance of all the second-level criteria from a panel of DMs via the following equation:

$$w_j = \sum_{k=1}^{t} \sigma_k w_j^k.$$ (16)

Step 4: Aggregate the individual opinion provided by a panel of DMs into the collective opinion, then employ following PFWA operator equation to construct an aggregated PF decision matrix $M = (\beta_{ij})_{m \times n}$.

$$\beta_{ij} = PFWA_{\sigma} (\beta_{ij}^{(1)}, \beta_{ij}^{(2)}, \ldots, \beta_{ij}^{(t)}) = \sigma_1 \beta_{ij}^{(1)} \oplus \sigma_2 \beta_{ij}^{(2)} \oplus \cdots \oplus \sigma_t \beta_{ij}^{(t)},$$
\[ Q(A_\Phi) - Q(A_p) \geq \Phi, \]  
\[ \text{(25)} \]

where \( \Phi = 1/(m - 1) \).

**Condition 2:** Conduct the “acceptable stability” to test whether the best ranked candidate based on \( Q_i \) is also the first ranked candidate consistent with \( S_i \) and \( R_i \).

So long as one of the conditions is not fulfilled, the parallel solutions are appeared.

**Step 10:** Utilize MRM to synthesize different ranks in accordance with differentiated \( \tau \). The specific enforcement process regarding MRM is portrayed in Fig. 3.

**FIGURE 3.** The process of MRM to reach the consensus rank of the green suppliers.

First, we construct the attribute-wise rank based on the ranking order results from each preference value \( \tau \), then capture the distance between the \( i^{th} \) alternative and the \( r^{th} \) rank via the following equation:

\[ p_{ir} = \sum_{\tau=1}^{g} w_\tau \cdot |z_{ir} - r|, \]  
\[ \text{(26)} \]

where \( z_{ir} \) describes the rank of \( i^{th} \) candidate regarding the \( \tau^{th} \) preference, \( r \) describes the \( r^{th} \) designated rank, and \( w_\tau \) describes the weight of the \( r^{th} \) rank.

Since the ratings on the criteria from individual DM are aggregated before employing the \( L_p \)-metric equation, the preferences from the individual DM should be taken into the overall value via the adjustment of \( \tau \). The OWA operator within normal distribution [72] has been verified as an effective way to lessen the unfair arguments by allocating smaller weight for “false” or “biased” argument. Hence, OWA is suitable to compute the weight of the \( r^{th} \) rank in accordance with the number of designated \( \tau \).
Second, we construct an \( m \times b - m \) distance matrix whose element represents the frequency that \( A_i \) is ranked the \( rth \) attribute-wise rank.

Third, we build a linear programming model to obtain an optimal permutation for the candidates. Since the core strategy of MRM is to acquire the overall ranking differs as little as possible from all available attribute-wise ranks. The element in \( m \times b \) distance matrix is expressed the distance of \( A_i \) from the given number of ranking. The smaller the distance is, the higher the consistency with the given number of ranking. Moreover, each candidate will be assigned to the given number ranking one time, we can utilize the binary integer, namely, \( q_{ir} \in \{0, 1\} \) to express the corresponding candidate assigned to the given number ranking or not. Hence, the problem is suitable to establish a linear programming model, the objective is to minimize sum product of \( p_{ir} \) and \( q_{ir} \), satisfying basic notion of MRM. For each provider is assigned for a given rank once, it follows that sum of \( q_{ir} \) equals to 1 for each given number ranking and each candidate, which are established as the constraints. The objective function and constraints are displayed as below:

\[
\begin{align*}
\text{min} & \sum_{i=1}^{m} \sum_{r=1}^{b} p_{ir} q_{ir} \\
\text{s.t.} & \sum_{r=1}^{b} q_{ir} = 1, \quad \sum_{i=1}^{m} q_{ir} = 1, \quad i, r = 1, 2, \cdots, m, \\
& q_{ir} \in \{0, 1\} \text{ for any } i \text{ and } r.
\end{align*}
\]

Finally, we obtain the optimal permutation \( q^* \) of the candidates, and utilize \( A_i \times q^* \) to identify the best solution.

V. A NUMERICAL CASE

A. DESCRIPTION OF THE EXAMPLE

To interpret the practicability and superiority of our AHP-VIKOR-MRM method for group green supplier selection within PF scenario, we choose a typical example in agri-food sector that makes important influence on the change of climate and environment. The corporation in this case is a leading edible oil manufacturer in China, who has been certified the ISO 14000, and complies the environmental protection guideline in daily operation activities. In practice, the case corporation intends to purchase the raw oil that is the main ingredient for the olive oil and comprises more than 90% of the total procurement costs. Therefore, this corporation should select an optimal green supplier.

In this example, six raw-oil available suppliers were identified via initial screening from the procurement and strategic sourcing department, namely, \( A_i = \{A_1, A_2, \cdots, A_6\} \). To handle the decision-making problem, the general manager of this company constitutes a panel of DMs, namely, \( E_k = \{E_1, E_2, E_3\} \). The evaluation criteria are sorted in subsection II. A., and the hierarchical criteria structure including the general objective, first-level criteria, and second-level criteria, is displayed in Fig. 4.

![FIGURE 4. A hierarchical structure for the group green supplier selection problem.](image-url)

B. DECISION PROCEDURE VIA THE PROPOSED METHOD

**Step 1:** Calculate the DM’s weights for the group green supplier selection problem. Linguistic variables used for the relative importance of DMs, are depicted in Fig. 2. Let \( \beta_k = P(\mu_k, \nu_k) \) denote the rating from the \( kth \) DM. Employ Eq. (10) to identify the \( kth \) DM weight, the acquired outcomes are placed in Table 4.

| Linguistic Variables | \( \sigma_1 \) | \( \sigma_2 \) | \( \sigma_3 \) |
|----------------------|---------------|---------------|---------------|
| Weights of DMs       | 0.3851        | 0.3411        | 0.2738        |

**Step 2:** Identify the criterion weights by the three DMs’ evaluation. We utilize the pairwise comparison matrix to represent a preference matrix in the form of multiplicative preference matrix. In this example, three DMs are invited to assess the intensity of criterion importance for this problem by the pairwise comparison scale [5]. The matrix is a multiplicative preference matrix and the available values in the matrix are the numbers of set \{1,2,3,4,5,6,7,8,9,1/2,1/3, 1/4,1/5,1/6,1/7,1/8,1/9\}. Utilize Eq. (12) to obtain the \( \lambda_{max} \), then employ Eqs. (13) and (14) to measure the inconsistency. If \( CR \) is not acceptable, we should employ Eq. (15) to improve the consistency of the multiplicative preference matrix. Then obtain the weights of criteria from three DMs, respectively. Finally, we aggregate the criterion weights at all levels based on the importance of involved DMs \( \sigma = (0.3851, 0.3411, 0.2738)^T \) determined by the general manager. The criterion weights from three DMs and the aggregated criterion weights are placed in Table 5. To facilitate understanding, we present the subcriterion weights graphically in Fig. 5.

**Step 3:** Build the aggregated PF decision-making matrix provided by three DMs. According to the linguistic variables for the rating of candidates depicted in Fig. 2, the DMs compare six green suppliers concerning the criteria, and provide their assessments displayed in Table 6. Then, we obtain a PF decision matrix from \( kth \) DM, expressed as \( M^k = (\beta^k_{ij})_{6 \times 15} \).
TABLE 5. Aggregated evaluation criteria weights at all levels from three DMs.

| General objective | The 1st level | The 2nd level | $w_j$ |
|-------------------|--------------|--------------|-------|
| $C_1$ Quality (0.449) | $C_{11}$ | 0.207 | 0.048 | 0.049 | 0.110 |
| $C_{12}$ | 0.131 | 0.245 | 0.223 | 0.195 |
| $C_{13}$ | 0.075 | 0.120 | 0.125 | 0.104 |
| $C_{14}$ | 0.036 | 0.036 | 0.051 | 0.040 |
| $C_2$ Service (0.250) | $C_{21}$ | 0.667 | 0.134 | 0.104 | 0.100 |
| $C_{22}$ | 0.123 | 0.066 | 0.074 | 0.090 |
| $C_{23}$ | 0.030 | 0.032 | 0.038 | 0.033 |
| $C_{24}$ | 0.031 | 0.018 | 0.034 | 0.027 |
| $C_3$ Price (0.152) | $C_{31}$ | 0.083 | 0.045 | 0.033 | 0.056 |
| $C_{32}$ | 0.040 | 0.082 | 0.096 | 0.069 |
| $C_{33}$ | 0.029 | 0.025 | 0.023 | 0.026 |
| $C_{34}$ | 0.035 | 0.010 | 0.014 | 0.021 |
| $C_4$ EMS (0.150) | $C_{41}$ | 0.055 | 0.082 | 0.075 | 0.070 |
| $C_{42}$ | 0.017 | 0.037 | 0.035 | 0.029 |
| $C_{43}$ | 0.042 | 0.020 | 0.025 | 0.030 |

where $β_{ij}^k$ describes the rating of $i$th candidate concerning $j$th criteria given by $k$th DM. The aggregated PF decision matrix $M = (β_{ij})_{6×15}$ is calculated by the preference and judgments from three DMs via Eq. (4), and the results of $M = (β_{ij})_{6×15}$ are listed in Table 7.

**Step 4:** Employ Eqs. (19) and (20) to identify $f^*_j$ and $f^-_j$ regarding the fifteen criteria. Owing to utilization of the linguistic variables relative to the superiority of ratings of the candidates, all criteria in the aggregated PF matrix are benefit criteria. The results of $f^*_j$ and $f^-_j$ on the fifteen criteria are listed in Table 8.

**Step 5:** Utilize Eq. (22) to compute $S_i$ that reflects the average gap for improvement priority, and employ Eq. (23) to compute $R_i$ that reflects the maximal gap for improvement priority. Then utilize Eq. (21) to obtain the distance $D_{ij}$. The results of $w_j D_{ij}$ are shown in Table 9, by means of which we can get the values of $S_i$, $S^*_i$, $S^-_i$, $R_i$, $R^*_i$ and $R^-_i$. The results of $S_i$, $R_i$, and their ranks are placed in Table 10.

**Step 6:** Employ Eq. (24) to compute $Q_i$ when $τ = 0.5$. The results of $Q_i$ and the corresponding ranks are displayed in Table 10. To facilitate understanding, we present the values of $S_i$, $R_i$, and $Q_i$ graphically in Fig. 6, from which we find the ranks based on $S_i$, $R_i$, and $Q_i$ are completely consistent. Subsequently, we can get $S^* = 0.1330$, $S^- = 0.9324$, $R^* = 0.0546$, and $R^- = 0.1950$.

If we change the preference parameter values of $τ$, we may obtain different results of $Q_i$, which shows the differentiated strategy of the tradeoff between “group utility” and

FIGURE 5. The weights of subcriteria for choosing the green supplier.
Table 8. $f^+$ and $f^-$ in aggregated PF decision matrix on each criterion.

| $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ |
|-------|-------|-------|-------|-------|
| $f^+$ | (0.92,0.30) | (0.77,0.30) | (0.74,0.34) | (0.74,0.34) | (0.74,0.33) |
| $f^-$ | (0.49,0.64) | (0.35,0.77) | (0.52,0.60) | (0.49,0.64) | (0.49,0.64) |

Table 9. Weighted distance values on each criterion.

| $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ |
|-------|-------|-------|-------|-------|-------|
| $A_1$ | 0.11  | 0.11  | 0.02  | 0.00  | 0.08  | 0.09  | 0.02  | 0.02  | 0.02  |
| $A_2$ | 0.04  | 0.01  | 0.00  | 0.03  | 0.06  | 0.02  | 0.01  | 0.01  | 0.00  |
| $A_3$ | 0.04  | 0.06  | 0.05  | 0.02  | 0.01  | 0.02  | 0.01  | 0.01  | 0.00  |
| $A_4$ | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.02  |
| $A_5$ | 0.10  | 0.20  | 0.10  | 0.04  | 0.07  | 0.05  | 0.02  | 0.02  | 0.06  |
| $A_6$ | 0.05  | 0.13  | 0.07  | 0.01  | 0.10  | 0.03  | 0.03  | 0.03  | 0.03  |

Table 10. Numerical results of $S_j$, $R_j$, $Q_j$, and corresponding ranks of this example (when $\tau = 0.5$).

| $S_j$ | $R_j$ | $Q_j$ | Rank | $Q_j$ | Rank |
|-------|-------|-------|------|-------|------|
| $A_1$ | 0.6205 | 0.1100 | 0.5022 | 4.00  | 4.00  |
| $A_2$ | 0.3143 | 0.0597 | 0.1314 | 2.00  | 2.00  |
| $A_3$ | 0.3366 | 0.0650 | 0.1642 | 3.00  | 3.00  |
| $A_4$ | 0.1330 | 0.0546 | 0.0000 | 1.00  | 1.00  |
| $A_5$ | 0.9324 | 0.1950 | 1.0000 | 6.00  | 6.00  |
| $A_6$ | 0.6270 | 0.1270 | 0.5668 | 5.00  | 5.00  |

“individual regret”. The results of $Q_j$ are finally obtained based on a set of $\tau = \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0\}$, displayed in Table 11. All the ranks of candidates according to the values of $Q_j$ are consistent, namely, $Q_4 > Q_2 > Q_3 > Q_1 > Q_6 > Q_5$.

Step 7: Test the “acceptable advantage” and “acceptable stability” according to the Eq. (25).

Condition 1: Test the “acceptable advantage”.

$\Phi = 1/(m-1) = 1/(6-1) = 0.2$.

When $\nu = 0.1$, $Q(A_2) - Q(A_4) = 0.0550 - 0 = 0.0550 < \Phi$, which couldn’t obtain $A_4 > A_2$.

$Q(A_3) - Q(A_4) = 0.0917 - 0 = 0.0917 < \Phi$, which couldn’t obtain $A_4 > A_3$.

$Q(A_1) - Q(A_4) = 0.4160 - 0 = 0.4160 > \Phi$, which can obtain $A_4 > A_1$.

$Q(A_5) - Q(A_1) = 0.5258 - 0.4160 = 0.1098 < \Phi$, which couldn’t obtain $A_5 > A_1$.

$Q(A_5) - Q(A_1) = 1 - 0.4160 = 0.5840 > \Phi$, which can obtain $A_1 > A_5$.

Condition 2: Conduct the “acceptable stability”.

According to the ranking order results of $S_j$ and $R_j$, namely, $S_4 > S_2 > S_3 > S_1 > S_6 > S_3$ and $R_4 > R_2 > R_3 > R_1 > R_6 > R_5$, the obtained ranking order result of this example is $\{A_2, A_3, A_4\} > \{A_1, A_6\} > \{A_5\}$ if $\tau = 0.1$. The optimal solution is $A_2, A_3, \text{and } A_4$.

All the ranks by PF-VIKOR method based on different values of $\tau$ are listed in Table 12. We find that when $\tau = \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6\}$, the ranks of green suppliers are same, namely, $\{A_2, A_3, A_4\} > \{A_1, A_6\} > \{A_5\}$; when $\tau = \{0.7, 0.8\}$, the ranking order results are same, namely, $\{A_2, A_4\} > \{A_3\} > \{A_1, A_6\} > \{A_5\}$; when $\tau = \{0.9, 1.0\}$, the ranking order results are same, namely, $\{A_4\} > \{A_2, A_3\} > \{A_1, A_6\} > \{A_5\}$.

Step 8: Apply MRM to integrate the different ranking order results with different values of parameter $\tau$. The attribute-wise ranks generated from Table 12 are shown in Table 13. When a tie occurs in the attribute-wise rank, a mean rank is allocated to the tied candidates. For instance, if $A_2, A_3$, and $A_4$ are tied for the first rank, the obtained ranking order result of this example is $\{A_2, A_3, A_4\} > \{A_1, A_6\} > \{A_5\}$; when $\tau = \{0.7, 0.8\}$, the ranking order results are same, namely, $\{A_2, A_4\} > \{A_3\} > \{A_1, A_6\} > \{A_5\}$; when $\tau = \{0.9, 1.0\}$, the ranking order results are same, namely, $\{A_4\} > \{A_2, A_3\} > \{A_1, A_6\} > \{A_5\}$.
A method under PF scenario, we will perform a comparison:

\[
F. \text{ Zhou, T.-Y. Chen: Integrated Multicriteria Group Decision-Making Approach for Green Supplier Selection Under PF Scenarios}
\]

**C. COMPARATIVE ANALYSIS**

To interpret the practicability of the AHP-VIKOR-MRM method under PF scenario, we will perform a comparison with the PF-WSM, PF-TOPSIS, and traditional PF-VIKOR methods using afore-mentioned example information in Subsection V.A.

First, we compare our integrated method with typical scoring model PF-WSM. We utilize Yager’s method [21] based on the following PFWA aggregation operator: \(Y(A_i) = P(\sum_{j=1}^{n} w_j \mu_j, \sum_{j=1}^{n} w_j v_j)\), where \(w_j\) describes the criterion weights shown in Table 5. And the obtained overall PFNs for the green suppliers are as follows:

\[
Y(A_1) = P(\sum_{j=1}^{15} w_j \mu_{ij}, \sum_{j=1}^{15} w_j v_{ij}) = P(0.6820, 0.5623),
\]

\[
Y(A_2) = P(\sum_{j=1}^{15} w_j \mu_{ij}, \sum_{j=1}^{15} w_j v_{ij}) = P(0.7822, 0.4551),
\]

\[
Y(A_3) = P(\sum_{j=1}^{15} w_j \mu_{ij}, \sum_{j=1}^{15} w_j v_{ij}) = P(0.7678, 0.4662),
\]

\[
Y(A_4) = P(\sum_{j=1}^{15} w_j \mu_{ij}, \sum_{j=1}^{15} w_j v_{ij}) = P(0.8422, 0.3879),
\]

\[
Y(A_5) = P(\sum_{j=1}^{15} w_j \mu_{ij}, \sum_{j=1}^{15} w_j v_{ij}) = P(0.5855, 0.6815),
\]

\[
Y(A_6) = P(\sum_{j=1}^{15} w_j \mu_{ij}, \sum_{j=1}^{15} w_j v_{ij}) = P(0.6809, 0.5725).
\]

Then, we employ Eq. (25) to construct the distance matrix, given the OWA weights \([22] w = (0.0443, 0.0719, 0.1034, 0.1317, 0.1487, 0.1487, 0.1317, 0.1034, 0.0719, 0.0443)^T\) corresponding to \(\tau = [0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0]\). The distance matrix is displayed as below:

\[
p_{ir} = \begin{bmatrix}
3.50 & 2.50 & 1.50 & 0.50 & 0.50 & 1.50 & 6.01 & 5.00 & 4.02 & 3.03 & 2.04 & 1.05 & 0.06 & 3.07 & 0.08 & 3.09 & 0.10
\end{bmatrix} A_1
\]

\[
A_2
\]

\[
A_3
\]

\[
A_4
\]

\[
A_5
\]

\[
A_6
\]

Then we employ Eq. (25) to construct the distance matrix, given the OWA weights \([22] w = (0.0443, 0.0719, 0.1034, 0.1317, 0.1487, 0.1487, 0.1317, 0.1034, 0.0719, 0.0443)^T\) corresponding to \(\tau = [0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0]\). The distance matrix is displayed as below:

\[
p_{ir} = \begin{bmatrix}
3.50 & 2.50 & 1.50 & 0.50 & 0.50 & 1.50 & 6.01 & 5.00 & 4.02 & 3.03 & 2.04 & 1.05 & 0.06 & 3.07 & 0.08 & 3.09 & 0.10
\end{bmatrix} A_1
\]

\[
A_2
\]

\[
A_3
\]

\[
A_4
\]

\[
A_5
\]

\[
A_6
\]

Then we employ Eq. (25) to construct the distance matrix, given the OWA weights \([22] w = (0.0443, 0.0719, 0.1034, 0.1317, 0.1487, 0.1487, 0.1317, 0.1034, 0.0719, 0.0443)^T\) corresponding to \(\tau = [0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0]\). The distance matrix is displayed as below:

\[
p_{ir} = \begin{bmatrix}
3.50 & 2.50 & 1.50 & 0.50 & 0.50 & 1.50 & 6.01 & 5.00 & 4.02 & 3.03 & 2.04 & 1.05 & 0.06 & 3.07 & 0.08 & 3.09 & 0.10
\end{bmatrix} A_1
\]

\[
A_2
\]

\[
A_3
\]

\[
A_4
\]

\[
A_5
\]

\[
A_6
\]

Then we employ Eq. (25) to construct the distance matrix, given the OWA weights \([22] w = (0.0443, 0.0719, 0.1034, 0.1317, 0.1487, 0.1487, 0.1317, 0.1034, 0.0719, 0.0443)^T\) corresponding to \(\tau = [0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0]\). The distance matrix is displayed as below:

\[
p_{ir} = \begin{bmatrix}
3.50 & 2.50 & 1.50 & 0.50 & 0.50 & 1.50 & 6.01 & 5.00 & 4.02 & 3.03 & 2.04 & 1.05 & 0.06 & 3.07 & 0.08 & 3.09 & 0.10
\end{bmatrix} A_1
\]

\[
A_2
\]

\[
A_3
\]

\[
A_4
\]

\[
A_5
\]

\[
A_6
\]
TABLE 14. Key indices and ranks among four PF MCGDM methods.

| PF WSM | PF TOPSIS | PF VIKOR |
|--------|-----------|----------|
| \( s(A_j) \) | Rank | \( RC(A_j) \) | Rank | Rank¹ | Rank² |
| \( A_1 \) | 0.1489 | 4 | 0.4057 | 5 | 4 | 4 |
| \( A_2 \) | 0.4047 | 2 | 0.6980 | 2 | 2 | 2 |
| \( A_3 \) | 0.3721 | 3 | 0.6755 | 3 | 2 | 3 |
| \( A_4 \) | 0.5588 | 1 | 0.8592 | 1 | 1 | 1 |
| \( A_5 \) | -0.122 | 6 | 0.1852 | 6 | 6 | 6 |
| \( A_6 \) | 0.1358 | 5 | 0.4283 | 4 | 4 | 4 |

Abbreviations: Rank from traditional PF VIKOR (Rank¹); Rank from our presented PF VIKOR (Rank²)

\( s(A_6) \) is very small, namely \( s(A_1) - s(A_6) = 0.0131 \). Meanwhile, in our proposed method, the faint disparity between \( Q_1 \) and \( Q_6 \) couldn’t pass the acceptable advantage test from all the preference values, then \( A_1 \) and \( A_6 \) are the parallel ranking.

Second, we compare our integrated method with the typical compromising model PF-TOPSIS. We should first determine the PFPIS (\( A^+ \)) and PFNIS (\( A^- \)) using the intersection and union operators from the classical TOPSIS. Then the obtained results of \( A^+ \) and \( A^- \) are the same as that of \( f^+ \) and \( f^- \) in PF-VIKOR method. Then we get the distances from the PFPIS \( D_Z(A_i, A^+) \) and PFNIS \( D_Z(A_i, A^-) \) employing the distance measure from Zhang and Xu [73], respectively. Finally, utilize relative closeness \( RC(A_i) = D_Z(A_i, A^+)/(D_Z(A_i, A^-) + D_Z(A_i, A^+)) \) to determine the ranks of candidates in the decreasing order. The results of \( RC(A_i) \) and ranks are displayed in Table 14, from which we find that the ranks of suppliers are \( A_4 \succ A_2 \succ A_3 \succ A_6 \succ A_1 \succ A_5 \), and the optimal solution is \( A_4 \). It is obviously seen that the ranking differences between PF-TOPSIS and our method focusing on \( A_1 \) and \( A_6 \) is similar from PF-WSM. Furthermore, the differences of \( A_1 \) and \( A_6 \) between PF-WSM and PF-TOPSIS lie in the affection from the reference point, namely, the score value from PF-WSM merely considers the membership degree and nonmembership degree, while the relative closeness from PF-TOPSIS considers the distance both from PFPIS and PFNIS.

Third, we compare our method with available PF-VIKOR method that utilizes the score and accuracy-based magnitude comparison method, and the basic Hamming distance measure from Zhang and Xu [73]. We first determine \( f^+_j \) and \( f^-_j \) using the score and accuracy-based method. The obtained \( f^+_j \) and \( f^-_j \) are the same as our method. However, the distance from \( f^+_j \) has some difference with our method, which results in different ranks if \( \tau \) is assigned as 0.8. The ranking order results are \( A_4 \succ A_2 \sim A_3 \succ A_1 \sim A_6 \succ A_5 \), the optimal green supplier is \( A_4 \). Furthermore, traditional PF-VIKOR merely considered one designated preference, which may emerge the preference loss in the group decision making. Then, the ranking between \( A_2 \) and \( A_3 \) couldn’t be distinguished the superiority. To facilitate comparison, we delineate the ranks from PF-WSM, PF-TOPSIS, traditional PF-VIKOR, and our presented methods graphically in Fig. 7.

Through comparative analysis, the core advantages of our AHP-VIKOR-MRM method under PF scenario are magnified as follows:

First, the score value from PF-WSM method directly considers the multiplication of the weights and the PFNs, but neglects the reference points. The PF-TOPSIS considers the PFPIS and PFNIS, but neglects the subjective preference of the DMs. Meanwhile, our presented method considers not only the reference points, but also the subjective preference, which indicates our method is more comprehensive, and may precisely obtain the optimal solution for the green supplier selection problem.

Second, the traditional PF-VIKOR method applies classical distance measure for PFNs [73], and the score and accuracy-based order relation [73], [82] in the \( L_\infty \)–metric equation. As the development of PF theory, the novel distance [69] considering both length distance and angular distance, the relative distance and reliable information-based order relation [68] has been demonstrated the effectiveness compared to the other magnitude comparison methods. Hence, our method can accurately reflect the unique properties of PFNs, and the subsequent solution for the green supplier selection problem is more accurate and reasonable.

Third, our hybrid AHP-VIKOR-MRM method may comprehensively reflect green supplier selection in practice, including establishing the hierarchical criteria system, the determining criterion weights to reflect DMs’ intention, utilizing PF-VIKOR method to rank the alternatives considering both objective assessments and subjective preference, employing MRM to arrive at the consensus opinion for different ranks, which can resolve the individual DM’s preference loss during the aggregation. Hence, our hybrid method is very suitable for choosing the appropriate green supplier.

VI. CONCLUSIONS AND FUTURE RESEARCH

Selecting the green supplier is a vital component in eco-supply chain, which can not only solve the dependence on supply chain, which can not only solve the dependence on
green raw materials, but also address the environmental problems in subsequent production process. This article proposes an integrated method combining the AHP, VIKOR, and MRM under PF scenario, which can effectively solve the group green supplier selection problem.

A. MANAGERIAL IMPLICATIONS

This article proposes a set of evaluation criteria and a novel AHP-VIKOR-MRM method with PF information to assess the green suppliers, and emphasizes managerial implications as below:

Firstly, a set of comprehensive hierarchical criteria is established to assess the green suppliers. Through in-depth observation regarding the aggregated criteria weights in Table 5, it is obvious seen that quality (C1) has the highest weight, accounting for 44.9%, and the subcriteria green product (19.5%), green material (11.0%), clean product (10.4%) play important role in the green supplier selection. Moreover, the subcriterion tangibles accounts for 10.0%, which also has obvious impact on the evaluation. From this perspective, the managers of the green suppliers should focus on the improvement of the quality and service, especially ensure the material, product, production be green, which can achieve both less impact on the environment, and acquire the sustainable development.

Secondly, the proposed integrated AHP-VIKOR-MRM method provides a framework to systematically assess the green suppliers. Our approach can assist DMs precisely selecting the optimal green supplier in the agri-food industry based on comprehensive hierarchical criteria structure under PF scenario, considering both less impact on the environment and maximum of economic benefits. Moreover, our proposed method can be extended to other aspects in eco-supply chain activities via adjusting the corresponding evaluation criteria, such as green product selection, green transportation selection, green warehouse selection, green packaging selection. Hence, our proposed method has strong applicability in eco-supply chain field, and can address the MCGDM problems more reliably and effectively, which promotes to construct the whole supply chain green, ecological, and sustainable.

B. FUTURE RESEARCH

This research presents the AHP-VIKOR-MRM method with PF information to address group green supplier evaluation problem. However, some limitations exist in our method. First, some new fuzzy information can describe the judgment more uncertain. To facilitate the flexibility of our technique, we can extend the PF information to the interval-valued PF information. Fermatean fuzzy information [87], q-rung orthopair fuzzy [88], triangular or trapezoidal PF information [14] to make the decision making more precisely. Second, we use the subjective criterion weights, but ignore the objectiveness. Enlightened by the objective criterion weight method [14], [40], [89], and hybrid criterion weight method [90], we will explore the hybrid weight method to comprehensively reflect the importance of the criteria. Third, we haven’t considered the interaction between membership and nonmembership of PFNs, we will draw lessons from the PF interaction power Bonferroni mean operator [79] to capture the interactions between membership and nonmembership function of PFNs, which may support DMs to acquire more reasonable decision results.

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FANG ZHOU received the B.S. degree in public service management from Nanjing Normal University, Nanjing, China, in 2003, and the M.S. degree in economic management from Suzhou University, Suzhou, China, in 2006. She is currently pursuing the Ph.D. degree in fuzzy decision theory with the Graduate Institute of Business and Management, Chang Gung University, supervised by Prof. Ting-Yu Chen. Recently, she focuses on multicriteria decision making and applications under Pythagorean fuzzy environment.

TING-YU CHEN received the B.S. degree in transportation engineering and management, the M.S. degree in civil engineering, and the Ph.D. degree in traffic and transportation from National Chiao Tung University, Taiwan. She is currently a Professor with the Department of Industrial and Business Management and the Graduate Institute of Business and Management, Chang Gung University, Taiwan. She is also an Adjunct Research Fellow with the Department of Nursing, Linkou Chang Gung Memorial Hospital, Taiwan. Her research interests include multiple criteria decision analysis, fuzzy decision analysis and methods, and consumer decision-making applications.