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ORIGINAL ARTICLE

Sustainable-supplier selection for manufacturing services: a failure mode and effects analysis model based on interval-valued fuzzy group decision-making

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Abstract Inside supply chains' exercises, evaluating suitable suppliers in light of the sustainability criteria, including economic, environmental, and social, can assist organizations to move toward sustainable development by considering their risks. Evaluating and choosing the sustainable-supplier for manufacturing services with lowest risks among candidates in the sustainable-supply chain management (S-SCM) is a vital issue for logistics managers, particularly by considering different sustainable criteria via three dimensions of the sustainability for strategic decisions. This paper introduces a new failure mode and effects analysis (FMEA) model based on multi-criteria decision-making by a group of supply chain-experts with interval-valued fuzzy (IVF) setting and asymmetric uncertainty information concurrently. In fact, the proposed model evaluates and ranks the suppliers according to their risks of economic, social, and environmental dimensions. Concepts of mean, variance, and skewness are introduced into the proposed FMEA model, and their mathematical relations are presented based on fuzzy possibilistic statistical concepts. Then, new definitions in the FMEA are presented for obtaining ideal solutions under uncertain conditions with possibilisic mean and possibilistic standard deviation, along with the possibilisic cube-root of skewness. Also, novel separation measures, max- and min-indices, and new fuzzy ranking index for risk scoring are presented to provide order of sustainable-supplier candidates under risky conditions. Finally, a real case study for manufacturing services is given and solved by the proposed FMEA model to demonstrate its capability in the S-SCM environment. The results of the proposed model illustrate that sustainable suppliers have been assessed and selected with the least amount of risks according to three dimensions of the sustainability.

Keywords Sustainable-supplier selection · Manufacturing services · Failure mode and effects analysis (FMEA) · Interval-valued fuzzy sets · Multi-criteria group decision-making (MCGDM) · Fuzzy possibilistic mean-variance-skewness

1 Introduction

The term supply chain management was described by Lambert et al. [30] as, "*the integration of key business processes from end-user through original suppliers, that provides products, services, and information that add value for customers and other stakeholders*." This meaning of sustainable-supply chain management (S-SCM) that depends on the triple bottom line and four supporting aspects of sustainability, including risk management, transparency, strategy, and culture, appeared in Fig. 1 [6].

Selecting suppliers are a vital issue of sustainable-supply chains and regard as a crucial concern in the usage of the S-SCM [29]. Vital necessity for companies in the recent years to stay in worldwide and information-based competition is to comprehend the significance, operational modes, procedure, and techniques for sustainable-supplier management [53].

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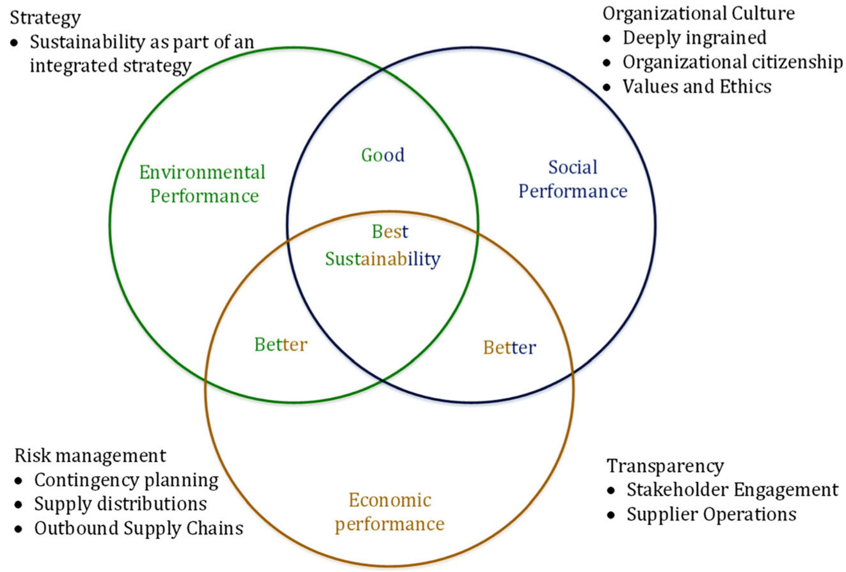

Fig. 1 Sustainable-supply chain management [6]

Sustainable-supplier management in this study may concentrate on how companies can evaluate and rank sustainable suppliers. In addition, uncertainties and risks of the S-SCM should be regarded for the appropriate evaluation and selection [3]. Supply chain risks are characterized as the occurrence of supply circumstances and events that can have crucial effects on the purchasing. Risk decreasing can be proficient by activates that either decrease the probability of possibly negative events or decrease the degree of negative effect ought to such events. There are two kinds of external risks: those that are directly related to a specific supplier, and those that influence a group of suppliers or a whole industry [3].

In this paper, a new fuzzy possibilistic-statistical decision model based on compromise solution modeling is introduced for the evaluation of sustainable-supplier candidates by comparability to interval-valued fuzzy-ideal solutions and asymmetric uncertainty information. Also, novel separation measures, new distance vectors, and ranking index are proposed according to three possibilisic-interval mean and possibilistic-interval standard deviation and possibilisic-interval cube-root of skewness, unlike the previous studies. Finally, it could help to support supply chain' experts in perceiving a best sustainable-supplier candidate systematically.

Proposed multi-criteria group decision-making (MCGDM) model in this paper for the sustainable-supplier selection is based on concepts of the Vlse Kriterijumska Optimizacija I Kompromisno Resenje in Serbian, meaning multiple criteria optimization and compromise solution (VIKOR) and multi-objective optimization on the basis of ratio analysis plus full multiplicative form (MULTIMOORA) methods as two well-known MCDM tools representing closeness to the ideal solution, with IVFSs. These two decision methods are widely applied to different industries in the related literature (e.g., [18, 24]). Both well-known decision methods (i.e., VIKOR and MULTIMOORA) can present a ranking list. The highest ranked candidate by these methods is the closest to the ideal solution. In fact, the concepts of the VIKOR and MULTIMOORA methods based on reference point and ratio system are taken into account in this paper because of more attention in the related literature along with ease of interpretation and simplicity in compromise decision-making modeling (e.g., [15, 19, 24, 47]).

The main novelties of this paper, in contrast to the previous studies on the extensions and applications of multi-criteria decision analysis methods under uncertainty for the sustainable-supplier evaluation and selection in the S-SCM are as follows:

(1) Presenting a new FMEA procedure within the MCDM framework under fuzzy possibilistic concepts with asymmetric uncertainty information;
(2) Presenting a new group decision-making process under an interval-valued fuzzy environment based on compromise solution modeling and three possibilistic mean, standard deviation, and the cube-root of skewness matrices;
(3) Proposing new definitions for obtaining positive and negative-ideal solutions with two high and low values of possibilisic mean, possibilistic standard deviation, and the cube-root of skewness with interval-valued fuzzy setting;
(4) Introducing novel separation measures based on possibilistic statistical concepts and new max-and min-indices for the sustainable-supplier selection problem;
(5) Presenting a new risk scoring index to provide a final order of sustainable-supplier candidates under the interval-valued fuzzy uncertainty; and

(6) Developing a possibilistic interval mean-entropy measure for computing the weight of each sustainable evaluation criterion with asymmetric uncertainty information.

The paper is structured as follows: Section 2 discusses the concepts and definitions; Section 3 describes the proposed methodology. An illustrative example on the S-SCM and a case study are presented in Section 4. Comparative analysis and managerial implications are given in Section 5. Section 6 comprises conclusions.

2 Related literature

2.1 Supply chain risks

Conventional supply chain risks include disruptions and delays caused by supply risks, such as supply capacity limitations, quality issues, supplier liquidity problems, supplier dependency, product design modifications, and delivery delays; procurement-related risks include exchange rates, inventories and stock outs, logistics, and transportation risks; supply chain relational risks include hold up risks and moral hazard, demand risks, such as demand volatility and inaccurate forecasts, information distortion and stock accumulation due to the bullwhip effect, and infrastructure and systems risks, such as breakdowns, equipment malfunctions [17].

The supply chain risks are categorized into two main groups: endogenous risks that are caused by organizations' activities along their supply chains and exogenous risks that are brought about to organizations by their interaction with external environment that they operate [16]. To evaluate and measure the risks in different systems and industries, failure mode and effects analysis (FMEA) as an analysis technique has been introduced in the related literature [44]. The FMEA is a structural and preventive reliability analysis model that regard known potential failure modes at one level, and takes their effects into account on the next and higher level of system hierarchy [43]. The main goal of the traditional FMEA is to identify potential failure modes, assess the causes and effects of several component failure modes, and determine what may eliminate or decrease the chance of failures. The computational results can assist analysts to identify and correct the failure modes that have a detrimental impact on the system and improve its performance during the phases of design and production [46].

2.2 FMEA approaches and applications

Regarding the recent works, Ashley et al. [1] presented the FMEA to assess the procedure in a social care context. They additionally introduced an examination of criticism from the FMEA team. Razavi Hajiagha et al. [23] considered a fuzzy belief structure approach that was based on VIKOR method and FMEA criteria, and then applied it to Tehran metro system successfully. Selim et al. [42] regarded a fuzzy TOPSIS method for evaluating the maintenance priorities of the machines and applied it to an international food company. Rah et al. [39] described a comparative analysis between traditional FMEA and a modified healthcare FMEA by considering the degree of congruence in detecting high-risk failures. Renu et al. [40] extended a knowledge-based modeling of applying the FMEA on flexible vehicle components. The proposed model was based on three-step knowledge discovery and data mining process to regard a set of rules. Lolli et al. [33] developed a modified FMEA to present the assignment of the scores regarding the occurrence factor more robust, and to connect the FMEA chart simply to the maintenance activities. Then, they applied it to a case study on blow molding process. Cabanes et al. [4] presented a study in STMicroelectronics manufacturing department in the engineering competences center located in Crolles, and described FMEA difficulties and improved FMEA approach. Sutrisno et al. [45] introduced a decision model that was based on SWOT analysis within the FMEA to provide the examination of competing risk-based improvement efforts. Chanamool and Naenna [7] considered the fuzzy FMEA for prioritization and evaluation of failures that could happen in the working procedure of an emergency department. Matusevych et al. [34] demonstrated the methods for tackling the issue of upgrading and efficiency of the technical servicing and repair of railway substation of electrified railways in operation by utilization of FMEA procedure.

The traditional FMEA considered risk priority numbers (RPNs) to assess and rank the risk of the failure modes that have been identified by a session of systematic brainstorming. The RPN is determined by computing the product of the occurrence (O), severity (S), and detection (D) of a failure, as $RPN = O \times S \times D$; where O is the probability of the failure, S is the severity of the failure, and D is the probability of the failure not being detected [43]. The three risk factors are all scaled by experts with an integer number from 1 to 10 based on commonly agreed evaluation criteria [46]. However, there are main shortcomings in the traditional FMEA as below: (1) The relative importance among O, S, and D is not taken into consideration; (2) Different combinations of O, S, and D may produce exactly the same value of RPN, but their hidden risk implications may be different; and (3) The three risk factors are difficult to be precisely evaluated.

2.3 Supplier selection problem

Wang et al. [48] considered a fuzzy hierarchical approach by technique for order of preference by similarity to ideal solution (TOPSIS) method for taking care of the issue of supplier selection to adapt fuzziness conditions and to give more goals and criteria' weights. Dalalah et al. [12] developed an integrated fuzzy model for group multi-criteria decision making (MCDM) in light of a changed fuzzy decision-making trial and evaluation laboratory (DEMATEL). They provided the criteria into two groups, especially, the cause group and the effect group. The exhibited integrated model was connected on an industrial case study at Nutridar Factory to show the proposed model. Samvedi et al. [41] considered an exertion toward quantifying the risks in a supply chain, and after that uniting the qualities into a comprehensive risk index. A coordinated approach, with a fuzzy analytical hierarchy process (AHP) and a fuzzy TOPSIS as its vital elements, has been utilized for this reason. A case study was utilized to represent the proposed approach. Chen and Wu [8] examined a modified failure mode and effects analysis (M-FMEA) technique to choose new suppliers from the supply chain risk's perspective and used the AHP technique to decide the weight of each criterion and sub-criterion for the supplier selection. An IC assembly company was provided to demonstrate this model.

Zhang et al. [53] reviewed the supplier selection literature with special focus on the background of sustainable-supply chain. Based on the literature review, the research gaps will be directed for additional inside and exploration. Paul [38] suggested a basic and easy to use supplier choice procedure for a supply chain which considers different selection criteria for managing supply risks. A rule-based fuzzy inference system (FIS) model was created. Risk factors were likewise consolidated in the model by creating fuzzy information and output criteria, and the best supplier was chosen by taking the aggregated supplier ranking index value into account. Goebel et al. [21] recognized elements for guiding purchasing and supply management behavior toward socially and environmentally sustainable-supplier evaluation. Results demonstrated that different elements of the firms' ethical culture can have significant effects on how purchasing managers account for social and environmental criteria when evaluating suppliers. Kumar Jauhar et al. [26] found a solution to the sustainable-supplier selection problem by differential evolution in pulp and paper industry to select the efficient sustainable suppliers, providing the maximum fulfillment for the sustainable criteria reported.

Orji and Wei [36] proposed a decision support approach for sustainable-supplier selection in manufacturing companies. Orji and Wei [37] regarded fuzzy sets and system dynamics concurrently in the sustainable-supplier selection. Then, a case study was provided in a gear manufacturing industry. Kumar Jauhar et al. [28] extended a data envelopment analysis (DEA)-based model with differential evolution regarding sustainable-supplier selection in pulp and paper industry. Giannakis and Papadopoulos [17] provided an operational point of view of supply chain sustainability, by regarding it as a risk management process. A mixed approach was received for data gathering and analysis. The FMEA technique was applied to evaluate the relative importance of the selected risks. Kumar et al. [29] utilized an integrated fuzzy AHP and fuzzy multi-objective optimization approach for order allocation among suppliers. The fuzzy AHP was utilized for weighing various factors, and weights of the factors were considered for the linear programming. Lin and Tseng [32] extended a hierarchical structure and linguistic preferences to distinguish the competitive priorities under the S-SCM in electronic central assembling firms in Taiwan. They considered an expert team with industrial experience, and presented to apply interval-valued fuzzy sets to represent the linguistic preferences and then used MCDM to assess the hierarchical structure in recognizing the ranking of competitive priorities. Further, in Table 1, a summary on sustainable-supply chain risks is provided according to the literature (i.e., [17, 25]).

The above-related literature on the sustainable-supplier selection problem denotes that an assessment of supplier problem is an MCDM framework in reality for the S-SCM. In fact, it is realized that sustainable-supplier selection cannot be influenced by only single factor; thus, numerous evaluation

Table 1 Sustainable-supply chain risks [25, 17]

	Environmental	Social	Economical
Endogenous	➢ Environmental accidents (e.g., fires, explosions) ➢ Pollution (air, water, soil) ➢ Non-compliance with sustainability laws ➢ Emission of greenhouse gases, ozone depletion ➢ Energy on consumption (unproductive use of energy) ➢ Excessive or unnecessary packaging ➢ Product waste	➢ Excessive working time; work-life imbalance ➢ Unfair wages ➢ Child labor/forced labor ➢ Discrimination (race, sex, religion, disability, age, political views) ➢ Healthy and safe working environment ➢ Exploitative hiring policies (lack of contract, insurance) ➢ Unethical treatment of animals	➢ Bribery ➢ False claims/dishonesty ➢ Price fixing accusations ➢ Antitrust claims ➢ Patent infringements ➢ Tax evasion
Exogenous	➢ Natural disasters (e.g., hurricanes, floods, earthquakes) ➢ Water scarcity ➢ Heatwaves, droughts	➢ Pandemic ➢ Social instability ➢ Demographic challenges/aging population	➢ Boycotts ➢ Litigations ➢ Energy prices volatility ➢ Financial crises

Table 2 Recent literature and their characteristics under uncertainty for sustainable-supplier selection problem

Studies	Characteristics of methods and approaches									Evaluation criteria		
	Crisp data	Fuzzy data	Interval-valued fuzzy data	Fuzzy possibilitic statistical approach	Asymmetric uncertainty information	Criteria weights	Linguistic terms	Group decision making	FMEA	Hybrid approach	Sustainable	Conventional
Wang et al. [48]	✓	✓				✓	✓	✓		✓		✓
Dalalah et al. [12]	✓	✓				✓	✓	✓		✓		✓
Samvedi et al. [41]	✓	✓				✓	✓	✓		✓		✓
Chen and Wu [8]	✓					✓	✓	✓	✓	✓		✓
Paul [38]	✓	✓				✓	✓					✓
Giannakis and Papadopoulos [17]	✓					✓			✓	✓	✓	✓
Lin and Tseng [32]	✓	✓	✓			✓	✓	✓		✓	✓	✓
Kumar et al. [29]	✓	✓				✓	✓	✓		✓	✓	✓
Proposed research	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

criteria can impact on this selection issue under uncertain conditions.

In Table 2, consequently, the gap of recent literature on the sustainable-supplier problem is provided in the S-SCM. In addition, in this paper the weaknesses of traditional FMEA method, including the relative importance among *O*, *S*, and *D*, risk implications in different combinations, and imprecise evaluation of three risk factors are identified and solved.

2.4 Motivation and significance

Managing risks and uncertainties in the assessment of sustainable-supplier candidates, considering diverse evaluation factors and taking care of the S-SCM' conditions are the fundamental concerns of the authors. For this reason, a new uncertain modeling based on interval-valued fuzzy sets and possibilitic statistical approach is proposed for the complex S-SCM decisions with comparability to ideal solutions. This fuzzy logic is more appropriate than classical modeling under uncertain conditions to indicate the level of uncertainty for each of sustainable-supplier candidates by an interval form. This uncertain modeling can prompt to extend the quality of sustainable-supplier selection and decision process, and to decrease the risk and low confidence in the S-SCM without cost-increasing.

In reality, proposed uncertain modeling can give more flexibility for the sustainable-supplier selection and evaluation to take account of the uncertain/vague data because of lack of information than the previous studies. Moreover, because of suppliers as an essential part of the S-SCM when the supply chain managers and planners are choosing them, new approaches to deal with risks and uncertainties can motivate the authors for applying different sustainable evaluation criteria and for focusing on the risk assessment in the S-SCM to select sustainable-supplier candidates that have less risk.

3 Basic concepts and definitions

Interval-valued fuzzy sets The interval-valued fuzzy numbers have been considered a special form of generalized fuzzy numbers [5, 9–11, 14, 22, 49]. According to Yao and Lin [50], an interval-valued triangular fuzzy number are represented as follows:

$$\tilde{A} = \left[\underset{\sim}{\tilde{A}}, \tilde{\tilde{A}}\right] = \left[\left(\underline{a}_1, \underline{a}_2, \underline{a}_3; \hat{\underline{h}}_{\tilde{A}}\right), \left(\bar{a}_1, \bar{a}_2, \bar{a}_3; \hat{\hat{h}}_{\tilde{A}}\right)\right] \quad (1)$$

Suppose $\underset{\sim}{A}$ and $\tilde{\tilde{A}}$ be two generalized triangular fuzzy numbers (GTFN); hence, $\hat{\underline{h}}_{\tilde{A}}$ and $\hat{\hat{h}}_{\tilde{A}}$ define the heights of $\tilde{A}\sim$ and $\tilde{\tilde{A}}\sim$, and $\underline{a}_1\underline{a}_2\underline{a}_3$, $\bar{a}_1\bar{a}_2\bar{a}_3$ define the real values.

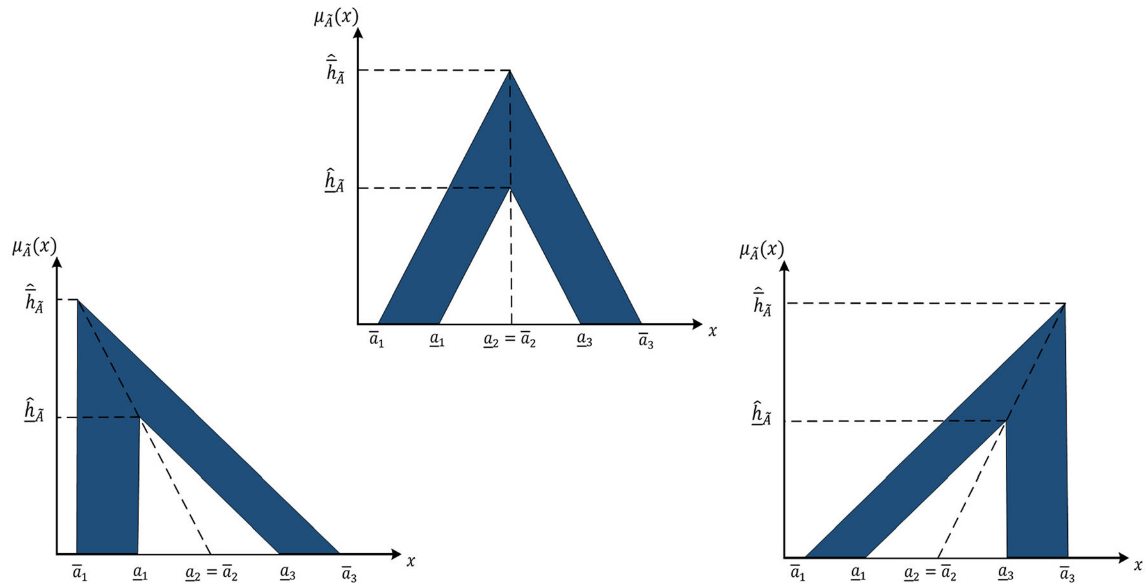

Fig. 2 Membership function of several interval-valued fuzzy numbers by considering the optimistic and pessimistic preferences

Possibility theory Some fundamental ideas and definitions about possibility theory are presented [13, 31, 51, 52]. Mean, variance, and skewness of triangular fuzzy variable $A = (a - \tau, a, a + \sigma)$ are provided as [27] in Eqs. (2)–(4):

$$E[A] = \frac{((a-\tau) + 2(a) + (a+\sigma))}{4} \tag{2}$$

$$V[A] = \frac{\left(33\alpha^3 + 21\alpha^2\beta + 11\alpha\beta^2 - \beta^3\right)}{(384\alpha)} \tag{3}$$

where $\alpha = \max\{((a) - (a-\tau)), ((a+\sigma) - (a))\}$ and $\beta = \min\{((a) - (a-\tau)), ((a+\sigma) - (a))\}$.and

$$S[A] = E\left[(A - E[A])^3\right] = \frac{((a+\sigma)-(a-\tau))^2}{32}[((a+\sigma)-(a))-((a)-(a-\tau))]. \tag{4}$$

In Fig. 2, membership function of several interval-valued fuzzy numbers is depicted by regarding the optimistic and pessimistic preferences.

4 Proposed FMEA approach for sustainable-supplier selection

In this section, a new FMEA procedure based on an interval-valued fuzzy group approach for the evaluation of sustainable suppliers is presented in the S-SCM environment based on possibility theory and statistical concepts. First, it is assumed that:

$TM = \{TM_k | k = 1, \ldots, p\}$ as a set of supply chain-team members or experts,
$S = \{S_l | l = 1, \ldots, u\}$ as a finite set of sustainable-supplier candidates,
$R = \{R_i | i = 1, \ldots, m\}$ as a finite set of risks of three dimensions of the sustainability for each sustainable supplier,
$C = \{C_j | j = 1, \ldots, n\}$ as a finite set of risk assessment criteria for the sustainable-supplier problem.

Since the information of sustainable-supplier candidates is uncertain during group decision making in the S-SCM, the supply chain-decision makers or experts can consider an interval-valued fuzzy (IVF) $\tilde{A}\sim_{ij}^{k}$ to estimate the judgment and opinion on sustainable risk R_i for each supplier (S_l) with respect to risk assessment criterion C_i. The MCGDM problem of sustainable-supplier selection according to risks of three dimensions of the sustainability with IVFSs and statistical concepts can be expressed in the matric form:

$$\tilde{A}^k = \left[\left[\left(\underline{a}_{ij_1}, \underline{a}_{ij_2}, \underline{a}_{ij_3}\right), \left(\bar{a}_{ij_1}, \bar{a}_{ij_2}, \bar{a}_{ij_3}\right)\right]^k\right]_{m \times n} = \\ = \begin{bmatrix} \left[\left(\underline{a}_{11_1}, \underline{a}_{11_2}, \underline{a}_{11_3}\right), \left(\bar{a}_{11_1}, \bar{a}_{11_2}, \bar{a}_{11_3}\right)\right]^k & \cdots & \left[\left(\left(\underline{a}_{1n_1}, \underline{a}_{1n_2}, \underline{a}_{1n_3}\right), \left(\bar{a}_{1n_1}, \bar{a}_{1n_2}, \bar{a}_{1n_3}\right)\right]^k \\ \vdots & \ddots & \vdots \\ \left[\left(\left(\underline{a}_{m1_1}, \underline{a}_{m1_2}, \underline{a}_{m1_3}\right), \left(\bar{a}_{m1_1}, \bar{a}_{m1_2}, \bar{a}_{m1_3}\right)\right]^k & \cdots & \left[\left(\underline{a}_{mn_1}, \underline{a}_{mn_2}, \underline{a}_{mn_3}\right), \left(\bar{a}_{mn_1}, \bar{a}_{mn_2}, \bar{a}_{mn_3}\right)\right]^k \end{bmatrix} \tag{5}$$

For convenience, we denote:

$$\left[\left(\underline{a}_{ij_1},\underline{a}_{ij_2},\underline{a}_{ij_3}\right),\left(\bar{a}_{ij_1},\bar{a}_{ij_2},\bar{a}_{ij_3}\right)\right]^k = \left[\left(\underline{a}_{ij}-\underline{\tau}_{ij},\underline{a}_{ij},\underline{a}_{ij}+\underline{\sigma}_{ij}\right),\left(\bar{a}_{ij}-\bar{\tau}_{ij},\bar{a}_{ij},\bar{a}_{ij}+\bar{\sigma}_{ij}\right)\right]^k$$

for kth $\mathrm{TM}\left(TM^k\right)$.

According to the above-mentioned descriptions, steps of the proposed interval-valued fuzzy FMEA procedure based on mean-variance-skewness concepts for the evaluation and selection problem of the sustainable suppliers according to risks of three dimensions of the sustainability are presented as follows:

Step 1. Proper risk assessment criteria are identified for the selection problem according to risks of three dimensions of the sustainability for each sustainable-supplier candidate ($l = 1, \ldots, u$).

Step 2. Provide the IVF-decision matrices of sustainable-supplier risks, and aggregate them for each sustainable-supplier candidate. The aggregated IVF-decision matrices of the sustainable-supplier risks are obtained by the arithmetic average with the following relation, respectively:

$$\underline{a}_{ijl} = \frac{1}{p}\sum_{k=1}^{p}\left(\underline{a}_{ij_l}\right)^k; l = 1,2,3 \quad \text{and } \bar{a}_{ijl} = \frac{1}{p}\sum_{k=1}^{p}\left(\bar{a}_{ij_l}\right)^k; l = 1,2,3 \tag{6}$$

Step 3. Transform the aggregated IVF-matrix into the normalized matrix of the sustainable-supplier risks. There are two criteria categories for the sustainable-supplier risks, namely benefit type and cost type. The higher the benefit type value is, the better it will be. It is opposite for the cost type. To transform different criteria scales into a comparable scale, the linear scale transformation method is used and presented by:

$$\tilde{a}'_{ij} = \left[\left(\underline{a}'_{ij_1},\underline{a}'_{ij_2},\underline{a}'_{ij_3}\right),\left(\bar{a}'_{ij_1},\bar{a}'_{ij_2},\bar{a}'_{ij_3}\right)\right] = \left[\left(\frac{\underline{a}_{ij}-\underline{\tau}_{ij}}{\left(\bar{a}_{ij}+\bar{\sigma}_{ij}\right)^+},\frac{\underline{a}_{ij}}{\left(\bar{a}_{ij}+\bar{\sigma}_{ij}\right)^+},\frac{\underline{a}_{ij}+\underline{\sigma}_{ij}}{\left(\bar{a}_{ij}+\bar{\sigma}_{ij}\right)^+}\right),\left(\frac{\bar{a}_{ij}-\bar{\tau}_{ij}}{\left(\bar{a}_{ij}+\bar{\sigma}_{ij}\right)^+},\frac{\bar{a}_{ij}}{\left(\bar{a}_{ij}+\bar{\sigma}_{ij}\right)^+},\frac{\bar{a}_{ij}+\bar{\sigma}_{ij}}{\left(\bar{a}_{ij}+\bar{\sigma}_{ij}\right)^+}\right)\right], j\in\Omega_b \tag{7}$$

and

$$\tilde{a}'_{ij} = \left[\left(\underline{a}'_{ij_1},\underline{a}'_{ij_2},\underline{a}'_{ij_3}\right),\left(\bar{a}'_{ij_1},\bar{a}'_{ij_2},\bar{a}'_{ij_3}\right)\right] = \left[\left(\frac{\left(\bar{a}_{ij}-\bar{\tau}_{ij}\right)^-}{\underline{a}_{ij}+\underline{\sigma}_{ij}},\frac{\left(\bar{a}_{ij}-\bar{\tau}_{ij}\right)^-}{\underline{a}_{ij}},\frac{\left(\bar{a}_{ij}-\bar{\tau}_{ij}\right)^-}{\underline{a}_{ij}+\underline{\tau}_{ij}}\right),\left(\frac{\left(\bar{a}_{ij}-\bar{\tau}_{ij}\right)^-}{\bar{a}_{ij}+\bar{\sigma}_{ij}},\frac{\left(\bar{a}_{ij}-\bar{\tau}_{ij}\right)^-}{\bar{a}_{ij}},\frac{\left(\bar{a}_{ij}-\bar{\tau}_{ij}\right)^-}{\bar{a}_{ij}-\bar{\tau}_{ij}}\right)\right], j\in\Omega_c \tag{8}$$

where Ω_b and Ω_c are the sets of benefit and cost criterion for the sustainable-supplier selection problem according to risks of three dimensions of the sustainability respectively, $\left(\bar{a}_{ij}+\bar{\sigma}_{ij}\right)^+ = \max_i\left(\bar{a}_{ij}+\bar{\sigma}_{ij}\right), i = 1,..,m$, $\left(\bar{a}_{ij}-\bar{\tau}_{ij}\right)^- = \min_i\left(\bar{a}_{ij}-\bar{\tau}_{ij}\right)$, $i = 1, \ldots, m$; $j = 1, \ldots, n$ and $k = 1, \ldots, p$. The maximum rating of each sustainable-supplier risk versus each criterion and the minimum rating using the normalization process can be obtained. For convenience, it is denoted as $\left[\left(\underline{a}'_{ij_1},\underline{a}'_{ij_2},\underline{a}'_{ij_3}\right),\left(\bar{a}'_{ij_1},\bar{a}'_{ij_2},\bar{a}'_{ij_3}\right)\right]^k = \left[\left(\underline{a}'_{ij}-\underline{\tau}'_{ij},\underline{a}'_{ij},\underline{a}'_{ij}+\underline{\sigma}'_{ij}\right),\left(\bar{a}'_{ij}-\bar{\tau}'_{ij},\bar{a}'_{ij},\bar{a}'_{ij}+\bar{\sigma}'_{ij}\right)\right]^k$ for kth TM.

Step 4. Construct the possibilistic interval mean matrix for the evaluation problem of the sustainable supplier risks. The possibilistic interval mean (m_{ij}) of IVF $\tilde{a}'_{ij} = \left[\left(\underline{a}'_{ij}-\underline{\tau}'_{ij},\underline{a}'_{ij},\underline{a}'_{ij}+\underline{\sigma}'_{ij}\right),\left(\bar{a}'_{ij}-\bar{\tau}'_{ij},\bar{a}'_{ij},\bar{a}'_{ij}+\bar{\sigma}'_{ij}\right)\right]$ are defined according to Eq. (2):

$$m_{ij} = \left(\underline{m}_{ij},\bar{m}_{ij}\right) = \left[\frac{\left(\left(\underline{a}'_{ij}-\underline{\tau}'_{ij}\right)+2\left(\underline{a}'_{ij}\right)+\left(\underline{a}'_{ij}-\underline{\sigma}'_{ij}\right)\right)}{4},\frac{\left(\left(\bar{a}'_{ij}-\bar{\tau}'^{U}_{ij}\right)+2\left(\bar{a}'_{ij}\right)+\left(\bar{a}'_{ij}+\bar{\sigma}'_{ij}\right)\right)}{4}\right] \tag{9}$$

Then, the possibilistic mean interval matrix is constructed for the evaluation problem of sustainable-supplier risks as follows:

$$M = [m_{ij}]_{m\times n} = \begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1n} \\ m_{21} & m_{22} & \cdots & m_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m_{m1} & m_{m2} & \cdots & m_{mn} \end{bmatrix} \tag{10}$$

Step 5. Construct the possibilistic interval standard deviation matrix the evaluation problem of sustainable-supplier risks.

The possibilistic interval standard deviation (sd_{ij}) of IVF $\tilde{a}'_{ij} = \left[\left(\underline{a}'_{ij}-\underline{\tau}'_{ij}, \underline{a}'_{ij}, \underline{a}'_{ij}+\underline{\sigma}'_{ij}\right), \left(\bar{a}'_{ij}-\bar{\tau}'_{ij}, \bar{a}'_{ij}, \bar{a}'_{ij}+\bar{\sigma}'_{ij}\right)\right]$ are determined according to Eq. (3):

$$sd_{ij} = \left[\underline{sd}_{ij}, \bar{sd}_{ij}\right] = \left[\sqrt{\frac{33\underline{\alpha}_{ij}^{3}+21\underline{\alpha}_{ij}^{2}\underline{\beta}_{ij}+11\underline{\alpha}_{ij}\underline{\beta}_{ij}^{2}-\underline{\beta}_{ij}^{3}}{384\underline{\alpha}_{ij}}}, \sqrt{\frac{33\bar{\alpha}_{ij}^{3}+21\bar{\alpha}_{ij}^{2}\bar{\beta}_{ij}+11\bar{\alpha}_{ij}\bar{\beta}_{ij}^{2}-\bar{\beta}_{ij}^{3}}{384\bar{\alpha}_{ij}}}\right] \tag{11}$$

$\underline{\alpha}_{ij}$,$\underline{\beta}_{ij}$, $\bar{\alpha}_{ij}$ and $\bar{\beta}_{ij}$ are determined according to the possibility theory in Section 2. Then, the possibilistic interval standard deviation matrix is constructed the evaluation problem of sustainable-supplier risks as follows:

$$SD = [sd_{ij}]_{m\times n} = \begin{bmatrix} sd_{11} & sd_{12} & \cdots & sd_{1n} \\ sd_{21} & sd_{22} & \cdots & sd_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ sd_{m1} & sd_{m2} & \cdots & sd_{mn} \end{bmatrix} \tag{12}$$

Step 6. Construct the possibilistic interval cube-root of skewness matrix of the selection problem of sustainable suppliers.

The possibilistic cube-root of skewness (Crs_{ij}) of IVF $\tilde{a}'_{ij} = \left[\left(\underline{a}'_{ij}-\underline{\tau}'_{ij}, \underline{a}'_{ij}, \underline{a}'_{ij}+\underline{\sigma}'_{ij}\right), \left(\bar{a}'_{ij}-\bar{\tau}'_{ij}, \bar{a}'_{ij}, \bar{a}'_{ij}+\bar{\sigma}'_{ij}\right)\right]$ are determined according to Eq. (4).

$$Crs_{ij} = \left[\underline{crs}_{ij}, \bar{crs}_{ij}\right] = \left[\sqrt[3]{\left(\frac{\left(\underline{\sigma}'_{ij}+\underline{\tau}'_{ij}\right)^{2}}{32}\right)\left(\underline{\sigma}'_{ij}-\underline{\tau}'_{ij}\right)}, \sqrt[3]{\left(\frac{\left(\bar{\sigma}'_{ij}+\bar{\tau}'_{ij}\right)^{2}}{32}\right)\left(\bar{\sigma}'_{ij}-\bar{\tau}'_{ij}\right)}\right] \tag{13}$$

Then, the possibilistic interval cube-root of skewness matrix is constructed for the selection problem of the sustainable supplier as follows:

$$CRS = [crs_{ij}]_{m\times n} = \begin{bmatrix} crs_{11} & crs_{12} & \cdots & crs_{1n} \\ crs_{21} & crs_{22} & \cdots & crs_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ crs_{m1} & crs_{m2} & \cdots & crs_{mn} \end{bmatrix} \tag{14}$$

Step 7. Calculate possibilistic interval mean-entropy measure of each sustainable evaluation criterion.

$$E_j = \left[\underline{e}_j, \bar{e}_j\right] = \left[-\frac{1}{Ln(m)}\sum_{i=1}^{m}\bar{m}'_{ij}Ln\left(\bar{m}'_{ij}\right), -\frac{1}{Ln(m)}\sum_{i=1}^{m}\underline{m}'_{ij}Ln\left(\underline{m}'_{ij}\right)\right] \tag{15}$$

where $\bar{m}'_{ij} = \left[\underline{m}'_{ij}.\bar{m}'_{ij}\right] = \left[\frac{\underline{m}_{ij}}{max_i\bar{m}_{ij}}.\frac{\bar{m}_{ij}}{max_i\bar{m}_{ij}}\right]$.

Step 8. Calculate proposed entropy weight based on the possibilistic mean with interval data.

$$W_j = \left[\underline{w}_j, \bar{w}_j\right] = \left[1-\bar{e}_j, 1-\underline{e}_j\right] \tag{16}$$

Step 9. Define positive-ideal and negative-ideal vectors (PIV and NIV) of possibilistic interval mean for the evaluation problem of sustainable-supplier risks. The PIV ($\check{M}^*$) and NIV ($\check{M}^-$) are calculated by:

$$M^* = \{M_1^*, M_2^*, \ldots, M_n^*\} = \left\{\left[\underline{m}_j^*, \bar{m}_j^*\right]\right\} = \left\{\max_i m_{ij} \middle| i = 1, 2, \ldots, m\right\} \tag{17}$$

$$M^- = \{M_1^-, M_2^-, \ldots, M_n^-\} = \left\{\left[\underline{m}_j^-, \bar{m}_j^-\right]\right\} = \left\{\min_i m_{ij} \middle| i = 1, 2, \ldots, m\right\} \tag{18}$$

Step 10. Define positive-ideal and negative-ideal vector (PIV and NIV) of possibilistic interval standard deviation. The PIV ($\bar{SD}^*$) and NIV ($\bar{SD}^-$) are determined by:

$$SD^* = \{SD_1^*, SD_2^*, \ldots, SD_n^*\} = \left\{\left[\underline{sd}_j^*, \bar{sd}_j^*\right]\right\} = \left\{\min_i sd_{ij} \middle| i = 1, 2, \ldots, m\right\} \tag{19}$$

and

$$SD^- = \{SD_1^-, SD_2^-, \ldots, SD_n^-\} = \left\{\left[\underline{sd}_j^-, \bar{sd}_j^-\right]\right\} = \left\{\max_i sd_{ij} \middle| i = 1, 2, \ldots, m\right\} \tag{20}$$

Step 11. Define positive-ideal and negative-ideal vector (PIV and NIV) of possibilistic interval cube-root of skewness. The PIV ($C\bar{R}S^*$) and NIV ($C\bar{R}S^-$) are determined by:

$$CRS^* = \{CRS_1^*, CRS_2^*, \ldots, CRS_n^*\} = \left\{\left[\underline{crs}_j^*, c\bar{r}s_j^*\right]\right\} = \left\{\min_i crs_{ij} \middle| i = 1, 2, \ldots, m\right\} \tag{21}$$

and

$$CRS^- = \{CRS_1^-, CRS_2^-, \ldots, CRS_n^-\} = \left\{\left[\underline{crs}_j^-, c\bar{r}s_j^-\right]\right\} = \left\{\max_i crs_{ij} \middle| i = 1, 2, \ldots, m\right\} \tag{22}$$

Step 12. Calculate the separation measures matrix of each sustainable-supplier risk according to possibilistic interval mean, standard deviation, and cube-root of skewness from the PIV (M^*, SD^*, CRS^*), respectively.

The separation vectors of possibilistic interval mean, standard deviation, and cube-root of skewness from the PIV are obtained for the evaluation problem of sustainable-supplier risks as below:

$$m_{D_{ij}^*}\left(m_{ij}, M_j^*\right) = \sqrt{\left(\underline{m}_j^* - \underline{m}_{ij}\right)^2 + \left(\bar{m}_j^* - \bar{m}_{ij}\right)^2} \tag{23}$$

$$sd_{D_{ij}^*}\left(sd_{ij}, SD_j^*\right) = \sqrt{\left(\underline{sd}_j^* - \underline{sd}_{ij}\right)^2 + \left(\bar{sd}_j^* - \bar{sd}_{ij}\right)^2} \tag{24}$$

$$crs_{D_{ij}^*}\left(crs_{ij}, CRS_j^*\right) = \sqrt{\left(\underline{crs}_j^* - \underline{crs}_{ij}\right)^2 + \left(c\bar{r}s_j^* - c\bar{r}s_{ij}\right)^2} \tag{25}$$

Step 13. Compute the separation measures matrix of each sustainable-supplier risk according to possibilistic interval mean, standard deviation, and cube-root of skewness number from the NIV (M^-, SD^-, CRS^-), respectively.

The separation vectors of possibilistic interval mean, standard deviation, and cube-root of skewness from the NIV are obtained for the evaluation problem of sustainable-supplier risks as below:

$$m_{D_{ij}^-}\left(m_{ij}, M_j^-\right) = \sqrt{\left(\underline{m}_j^- - \underline{m}_{ij}\right)^2 + \left(\bar{m}_j^- - \bar{m}_{ij}\right)^2} \tag{26}$$

$$sd_{D_{ij}^-}\left(sd_{ij}, SD_j^-\right) = \sqrt{\left(\underline{sd}_j^- - \underline{sd}_{ij}\right)^2 + \left(\bar{sd}_j^- - \bar{sd}_{ij}\right)^2} \tag{27}$$

$$crs_{D_{ij}^-}\left(crs_{ij}, CRS_j^-\right) = \sqrt{\left(\underline{crs}_j^- - \underline{crs}_{ij}\right)^2 + \left(c\bar{r}s_j^- - c\bar{r}s_{ij}\right)^2} \tag{28}$$

Step 14. Calculate proposed indices values of S_i^M, S_i^{SD}, S_i^{CRS}, R_i^M, R_i^{SD}, and R_i^{CRS} for sustainable-supplier risks according to mean, standard deviation, and cube-root of skewness ($i = 1, 2, \ldots, m$).

$$\left[\left(\underline{S}_i^M\right)^+, \left(\bar{S}_i^M\right)^+\right] = \left[\sum_{j=1}^{n} \frac{\underline{w}_j \times m_{D_{ij}^*}\left(m_{ij}, M_j^*\right)}{\sqrt{\left(\underline{m}_j^* - \underline{m}_j^-\right)^2 + \left(\bar{m}_j^* - \bar{m}_j^-\right)^2}}, \sum_{j=1}^{n} \frac{\bar{w}_j \times m_{D_{ij}^*}\left(m_{ij}, M_j^*\right)}{\sqrt{\left(\underline{m}_j^* - \underline{m}_j^-\right)^2 + \left(\bar{m}_j^* - \bar{m}_j^-\right)^2}}\right] \tag{29}$$

$$\left[\left(\underline{S}_i^{SD}\right)^+, \left(\bar{S}_i^{SD}\right)^+\right] = \left[\sum_{j=1}^{n} \frac{\underline{w}_j \times sd_{D_{ij}^*}\left(sd_{ij}, SD_j^*\right)}{\sqrt{\left(\underline{sd}_j^- - \underline{sd}_j^*\right)^2 + \left(\bar{sd}_j^- - \bar{sd}_j^*\right)^2}}, \sum_{j=1}^{n} \frac{\bar{w}_j \times sd_{D_{ij}^*}\left(sd_{ij}, SD_j^*\right)}{\sqrt{\left(\underline{sd}_j^- - \underline{sd}_j^*\right)^2 + \left(\bar{sd}_j^- - \bar{sd}_j^*\right)^2}}\right] \tag{30}$$

$$\left[\left(\underline{S}_i^{CRS}\right)^+, \left(\bar{S}_i^{CRS}\right)^+\right] = \left[\sum_{j=1}^{n} \frac{\underline{w}_j \times crs_{D_{ij}^*}\left(crs_{ij}, CRS_j^*\right)}{\sqrt{\left(\underline{crs}_j^- - \underline{crs}_j^*\right)^2 + \left(\bar{crs}_j^- - \bar{crs}_j^*\right)^2}}, \sum_{j=1}^{n} \frac{\bar{w}_j \times crs_{D_{ij}^*}\left(crs_{ij}, CRS_j^*\right)}{\sqrt{\left(\underline{crs}_j^- - \underline{crs}_j^*\right)^2 + \left(\bar{crs}_j^- - \bar{crs}_j^*\right)^2}}\right] \tag{31}$$

$$\left[\left(\underline{S}_i^M\right)^-, \left(\bar{S}_i^M\right)^-\right] = \left[\sum_{j=1}^{n} \frac{\underline{w}_j \times m_{D_{ij}^-}\left(m_{ij}, M_j^-\right)}{\sqrt{\left(\underline{m}_j^* - \underline{m}_j^-\right)^2 + \left(\bar{m}_j^* - \bar{m}_j^-\right)^2}}, \sum_{j=1}^{n} \frac{\bar{w}_j \times m_{D_{ij}^-}\left(m_{ij}, M_j^-\right)}{\sqrt{\left(\underline{m}_j^* - \underline{m}_j^-\right)^2 + \left(\bar{m}_j^* - \bar{m}_j^-\right)^2}}\right] \tag{32}$$

$$\left[\left(\underline{S}_i^{SD}\right)^-, \left(\bar{S}_i^{SD}\right)^-\right] = \left[\sum_{j=1}^{n} \frac{\underline{w}_j \times sd_{D_{ij}^-}\left(sd_{ij}, SD_j^-\right)}{\sqrt{\left(\underline{sd}_j^- - \underline{sd}_j^*\right)^2 + \left(\bar{sd}_j^- - \bar{sd}_j^*\right)^2}}, \sum_{j=1}^{n} \frac{\bar{w}_j \times sd_{D_{ij}^-}\left(sd_{ij}, SD_j^-\right)}{\sqrt{\left(\underline{sd}_j^- - \underline{sd}_j^*\right)^2 + \left(\bar{sd}_j^- - \bar{sd}_j^*\right)^2}}\right] \tag{33}$$

$$\left[\left(\underline{S}_i^{CRS}\right)^-, \left(\bar{S}_i^{CRS}\right)^-\right] = \left[\sum_{j=1}^{n} \frac{\underline{w}_j \times crs_{D_{ij}^-}\left(crs_{ij}, CRS_j^-\right)}{\sqrt{\left(\underline{crs}_j^- - \underline{crs}_j^*\right)^2 + \left(\bar{crs}_j^- - \bar{crs}_j^*\right)^2}}, \sum_{j=1}^{n} \frac{\bar{w}_j \times crs_{D_{ij}^-}\left(crs_{ij}, CRS_j^-\right)}{\sqrt{\left(\underline{crs}_j^- - \underline{crs}_j^*\right)^2 + \left(\bar{crs}_j^- - \bar{crs}_j^*\right)^2}}\right] \tag{34}$$

$$\left[\left(\underline{R}_i^M\right)^+, \left(\bar{R}_i^M\right)^+\right] = \left[\max_j \frac{\underline{w}_j \times m_{D_{ij}^*}\left(m_{ij}, M_j^*\right)}{\sqrt{\left(\underline{m}_j^* - \underline{m}_j^-\right)^2 + \left(\bar{m}_j^* - \bar{m}_j^-\right)^2}}, \max_j \frac{\bar{w}_j \times m_{D_{ij}^*}\left(m_{ij}, M_j^*\right)}{\sqrt{\left(\underline{m}_j^* - \underline{m}_j^-\right)^2 + \left(\bar{m}_j^* - \bar{m}_j^-\right)^2}}\right] \tag{35}$$

$$\left[\left(\underline{R}_i^{SD}\right)^+, \left(\bar{R}_i^{SD}\right)^+\right] = \left[\max_j \frac{\underline{w}_j \times sd_{D_{ij}^*}\left(sd_{ij}, Sd_j^*\right)}{\sqrt{\left(\underline{sd}_j^- - \underline{sd}_j^*\right)^2 + \left(\bar{sd}_j^- - \bar{sd}_j^*\right)^2}}, \max_j \frac{\bar{w}_j \times sd_{D_{ij}^*}\left(sd_{ij}, SD_j^*\right)}{\sqrt{\left(\underline{sd}_j^- - \underline{sd}_j^*\right)^2 + \left(\bar{sd}_j^- - \bar{sd}_j^*\right)^2}}\right] \quad (36)$$

$$\left[\left(\underline{R}_i^{CRS}\right)^+, \left(\bar{R}_i^{CRS}\right)^+\right] = \left[\max_j \frac{\underline{w}_j \times crs_{D_{ij}^*}\left(crs_{ij}, CRS_j^*\right)}{\sqrt{\left(\underline{crs}_j^- - \underline{crs}_j^*\right)^2 + \left(\bar{crs}_j^- - \bar{crs}_j^*\right)^2}}, \max_j \frac{\bar{w}_j \times crs_{D_{ij}^*}\left(crs_{ij}, CRS_j^*\right)}{\sqrt{\left(\underline{crs}_j^- - crs_j^*\right)^2 + \left(\bar{crs}_j^- - \bar{crs}_j^*\right)^2}}\right] \quad (37)$$

$$\left[\left(\underline{R}_i^{M}\right)^-, \left(\bar{R}_i^{M}\right)^-\right] = \left[\max_j \frac{\underline{w}_j \times m_{D_{ij}^-}\left(m_{ij}, M_j^-\right)}{\sqrt{\left(\underline{m}_j^* - \underline{m}_j^-\right)^2 + \left(\bar{m}_j^* - \bar{m}_j^-\right)^2}}, \max_j \frac{\bar{w}_j \times m_{D_{ij}^-}\left(m_{ij}, M_j^-\right)}{\sqrt{\left(\underline{m}_j^* - \underline{m}_j^-\right)^2 + \left(\bar{m}_j^* - \bar{m}_j^-\right)^2}}\right] \quad (38)$$

$$\left[\left(\underline{R}_i^{SD}\right)^-, \left(\bar{R}_i^{SD}\right)^-\right] = \left[\max_j \frac{\underline{w}_j \times sd_{D_{ij}^-}\left(sd_{ij}, SD_j^-\right)}{\sqrt{\left(\underline{sd}_j^- - \underline{sd}_j^*\right)^2 + \left(\bar{sd}_j^- - \bar{sd}_j^*\right)^2}}, \max_j \frac{\bar{w}_j \times sd_{D_{ij}^-}\left(sd_{ij}, SD_j^-\right)}{\sqrt{\left(\underline{sd}_j^- - \underline{sd}_j^*\right)^2 + \left(\bar{sd}_j^- - \bar{sd}_j^*\right)^2}}\right] \quad (39)$$

$$\left[\left(\underline{R}_i^{CRS}\right)^-, \left(\bar{R}_i^{CRS}\right)^-\right] = \left[\max_j \frac{\underline{w}_j \times crs_{D_{ij}^-}\left(crs_{ij}, CRS_j^-\right)}{\sqrt{\left(\underline{crs}_j^* - \underline{crs}_j^-\right)^2 + \left(\bar{crs}_j^* - \bar{crs}_j^-\right)^2}}, \max_j \frac{\bar{w}_j \times crs_{D_{ij}^-}\left(crs_{ij}, CRS_j^-\right)}{\sqrt{\left(\underline{crs}_j^* - \underline{crs}_j^-\right)^2 + \left(\bar{crs}_j^* - \bar{crs}_j^-\right)^2}}\right] \quad (40)$$

Step 15. Compute the following proposed max-and min-indices.

$$\chi^* = \min_i \left(\frac{\left(\underline{S}_i^M\right)^+ + \left(\underline{S}_i^{SD}\right)^+ + \left(\underline{S}_i^{CRS}\right)^+}{3}\right) \quad (41)$$

$$\chi^- = \max_i \left(\frac{\left(\bar{S}_i^M\right)^+ + \left(\bar{S}_i^{SD}\right)^+ + \left(\bar{S}_i^{CRS}\right)^+}{3}\right) \quad (42)$$

$$\vartheta^* = \min_i \left(\frac{\left(\underline{R}_i^M\right)^+ + \left(\underline{R}_i^{SD}\right)^+ + \left(\underline{R}_i^{CRS}\right)^+}{3}\right) \quad (43)$$

$$\vartheta^- = \max_i \left(\frac{\left(\bar{R}_i^M\right)^+ + \left(\bar{R}_i^{SD}\right)^+ + \left(\bar{R}_i^{CRS}\right)^+}{3}\right) \quad (44)$$

$$\psi^* = \max_i \left(\frac{\left(\bar{S}_i^M\right)^- + \left(\bar{S}_i^{SD}\right)^- + \left(\bar{S}_i^{CRS}\right)^-}{3}\right) \quad (45)$$

$$\psi^- = \min_i \left(\frac{\left(\underline{S}_i^M\right)^- + \left(\underline{S}_i^{SD}\right)^- + \left(\underline{S}_i^{CRS}\right)^-}{3}\right) \quad (46)$$

$$\delta^* = \max_i \left(\frac{\left(\bar{R}_i^M\right)^- + \left(\bar{R}_i^{SD}\right)^- + \left(\bar{R}_i^{CRS}\right)^-}{3}\right) \quad (47)$$

$$\delta^{-} = \min_{i}\left(\frac{\left(\underline{R}_i^{M}\right)^{-} + \left(\underline{R}_i^{SD}\right)^{-} + \left(\underline{R}_i^{CRS}\right)^{-}}{3}\right) \tag{48}$$

Step 16. Calculate I_i and P_i values of each sustainable-supplier risk ($i = 1, 2, \ldots, m$).

$$I_i = \frac{\nu}{2} \times \left[\frac{\left(\frac{\left(\underline{S}_i^{M}\right)^{+} + \left(\underline{S}_i^{SD}\right)^{+} + \left(\underline{S}_i^{CRS}\right)^{+}}{3}\right) - \chi^{*}}{\chi^{-} - \chi^{*}} + \frac{\left(\frac{\left(\bar{S}_i^{M}\right)^{+} + \left(\bar{S}_i^{SD}\right)^{+} + \left(\bar{S}_i^{CRS}\right)^{+}}{3}\right) - \chi^{*}}{\chi^{-} - \chi^{*}}\right] + \frac{(1-\nu)}{2} \times \left[\frac{\left(\frac{\left(\underline{R}_i^{M}\right)^{+} + \left(\underline{R}_i^{SD}\right)^{+} + \left(\underline{R}_i^{CRS}\right)^{+}}{3}\right) - \vartheta^{*}}{\vartheta^{-} - \vartheta^{*}} + \frac{\left(\frac{\left(\bar{R}_i^{M}\right)^{+} + \left(\bar{R}_i^{SD}\right)^{+} + \left(\bar{R}_i^{CRS}\right)^{+}}{3}\right) - \vartheta^{*}}{\vartheta^{-} - \vartheta^{*}}\right] \tag{49}$$

$$\frac{\mu}{2} \times \left[\frac{\left(\frac{\left(\underline{S}_i^{M}\right)^{-} + \left(\underline{S}_i^{SD}\right)^{-} + \left(\underline{S}_i^{CRS}\right)^{-}}{3}\right) - \psi^{-}}{\psi^{*} - \psi^{-}} + \frac{\left(\frac{\left(\bar{S}_i^{M}\right)^{-} + \left(\bar{S}_i^{SD}\right)^{-} + \left(\bar{S}_i^{CRS}\right)^{-}}{3}\right) - \psi^{-}}{\psi^{*} - \psi^{-}}\right] + \frac{(1-\mu)}{2} \times \left[\frac{\left(\frac{\left(\underline{R}_i^{M}\right)^{-} + \left(\underline{R}_i^{SD}\right)^{-} + \left(\underline{R}_i^{CRS}\right)^{-}}{3}\right) - \delta^{-}}{\delta^{*} - \delta^{-}} + \frac{\left(\frac{\left(\bar{R}_i^{M}\right)^{-} + \left(\bar{R}_i^{SD}\right)^{-} + \left(\bar{R}_i^{CRS}\right)^{-}}{3}\right) - \delta^{-}}{\delta^{*} - \delta^{-}}\right] \tag{50}$$

where ν and μ are introduced as weight of the strategy of the majority of criteria or the maximum group utility. The values of ν and μ fall within the range of 0 to 1, and these strategies can be compromised by ν=0.5 and $\mu = 0.5$ for the sustainable-supplier selection problem.

Step 17. Compute final proposed score (T_i) of the risks for each sustainable-supplier candidate according to the preference order. The minimum value of the T_i (risks score) demonstrates the better performance for the sustainable-supplier candidate (S_l), φ within the range of 0 to 1.

$$T_i = \varphi I_i + (1-\varphi)(1/P_i) \tag{51}$$

Eq. (51) presents a compromise solution for the sustainable-supplier risk.

Step 18. Sustainable-supplier candidates are ranked by increasing sorting of *score*(S_l) values, $l = 1, \ldots, u$, as below:

$$Score(S_l) = \sum_{i=1}^{m} T_i \ ; \ \forall l \tag{52}$$

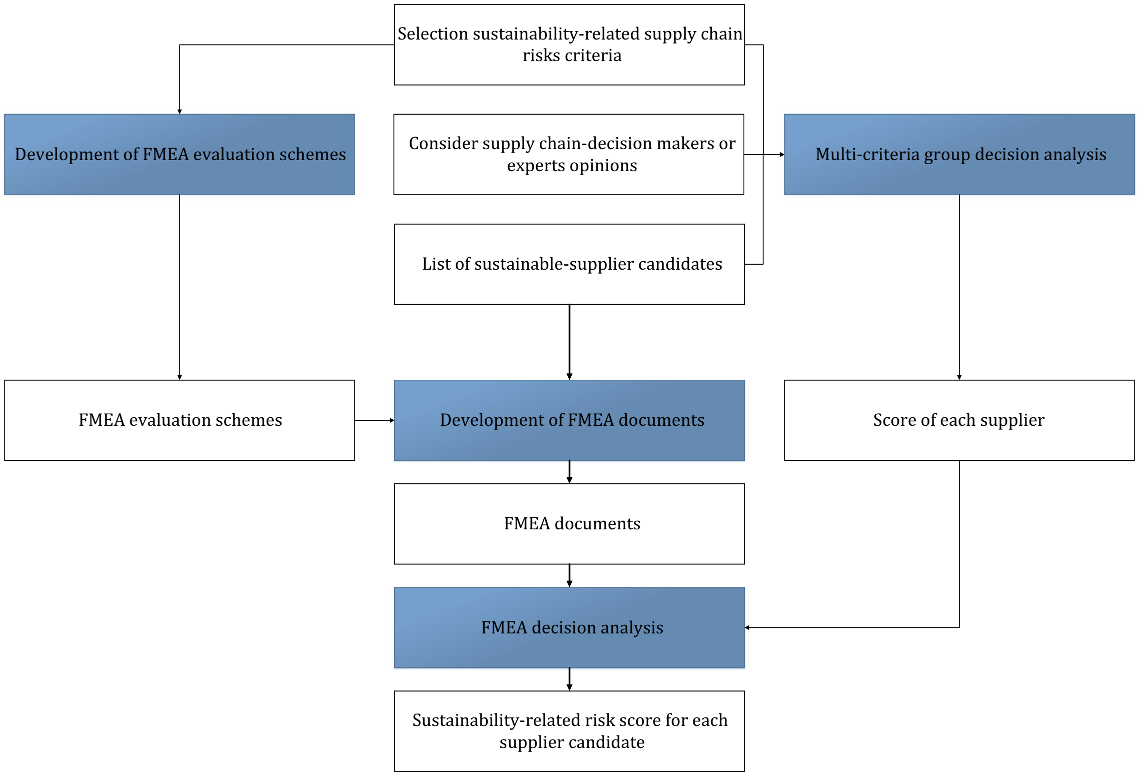

Fig. 3 Flowchart of the proposed FMEA procedure

In Fig. 3, a flowchart of the proposed FMEA procedure is given. This figure demonstrates the workflow of the proposed approach of this paper. The white boxes denote the input and output information, and the color boxes show the particular methodical procedure. In the box of development of FMEA evaluation schemes, the FMEA team categorizes different risk situations and characterizes the ranking schemes for the RPN. In the box of development of FMEA documents, each supplier is appraised by the FMEA evaluation schemes, and the final documents capture the conventional information from the FMEA, for example, failure modes, and causes and effects.

The box of multi-criteria group decision analysis demonstrates the conventional assessments within MCGDM framework for sustainable-supplier selection by a group of professional experts. The main contributions of this paper are in the group decision analysis process. The detailed presentations

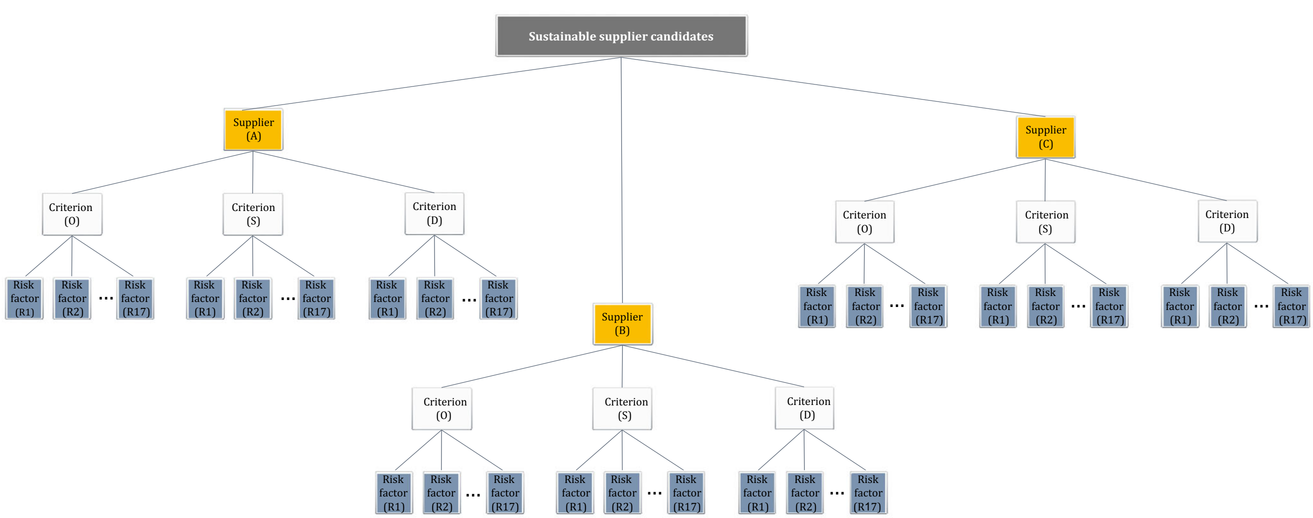

Fig. 4 Main differences of this procedure compared to the traditional FMEA

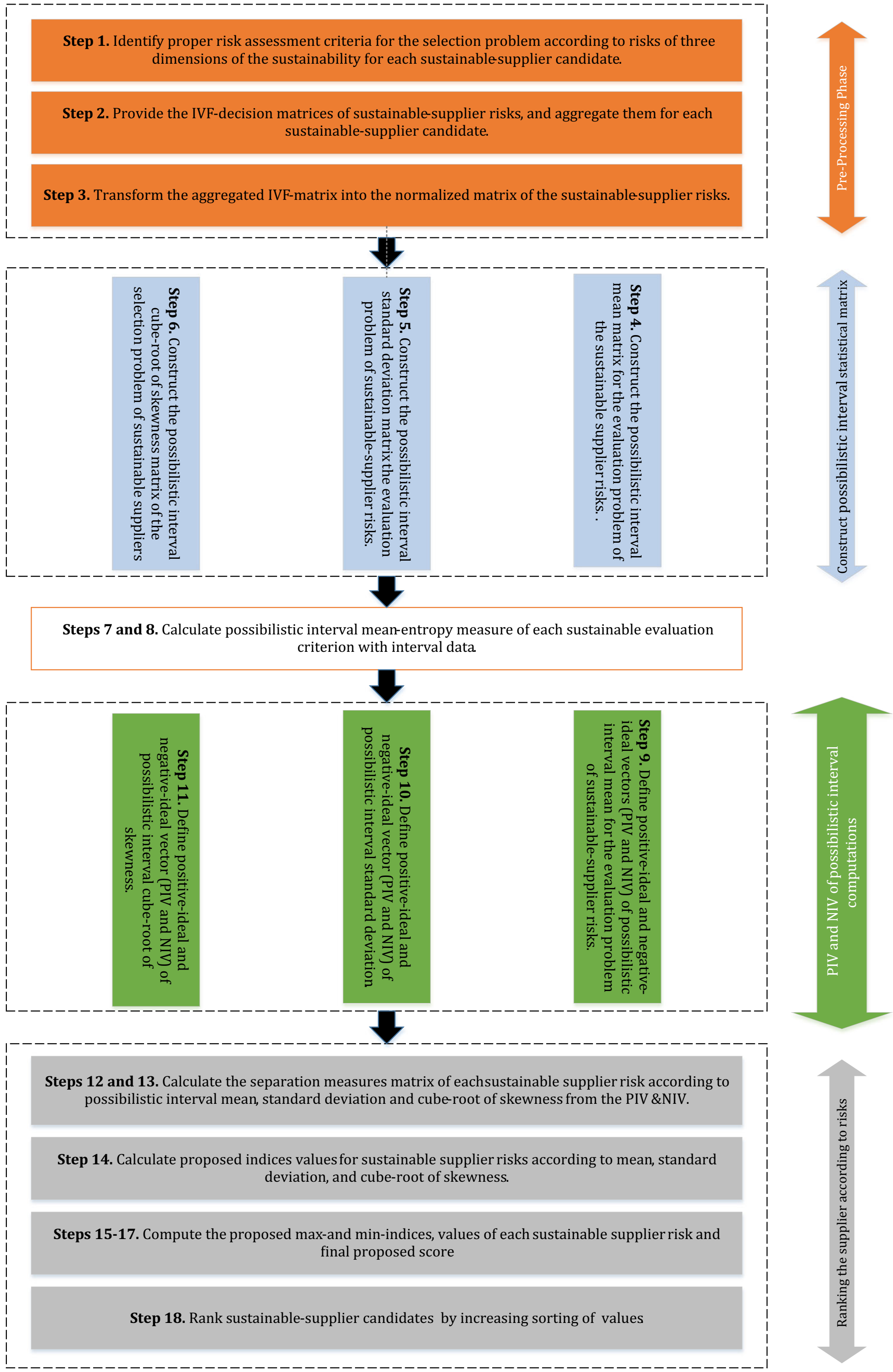

Fig. 5 Hierarchical structure of the FMEA-decision problem

are depicted in Fig. 4. The main differences of this procedure compared to the traditional FMEA are presented in Fig. 4. Then, in the box of FMEA decision analysis, the quantitative information from the FMEA documents is used to examine the first scores of sustainable suppliers as indicated by their risk situations. Then, scores are provided for the final choice.

5 Application of the proposed FMEA approach for manufacturing services

To illustrate the proposed interval-valued fuzzy FMEA procedure, a real case study from the recent literature [8] is adopted and provided for the selection problem. Major changes in the

Table 3 Linguistic variables for the values of the sustainable-supplier candidates' risks [2]

Linguistic variables	Interval-valued fuzzy numbers
Very Poor (VP)	[(0.00,0.00,1.00), (0.00,0.00,1.50)]
Poor (P)	[(0.50,1.00,2.50), (0.00,1.00,3.50)]
Moderately Poor (MP)	[(1.50,3.00,4.50), (0.00,3.00,5.50)]
Fair (F)	[(3.50,5.00,6.50), (2.50,5.00,7.50)]
Moderately Good (MG)	[(5.50,7.00,8.00), (4.50,7.00,9.50)]
Good (G)	[(7.50,9.00,9.50), (5.50,9.00,10.00)]
Very Good (VG)	[(9.50,10.00,10.00), (8.50,10.00,10.00)]

business environment, such as business globalization and rapid changes in technology, have increased competition and difficulty of the management in organizations. In today's business environment, managers and staff should have the ability to deal with internal relationships and dependencies between departments and chains' vague and complex along with data, tasks, activities, processes, and people to meet. In such a complex environment, organizations need managers who have the inherent complexity in terms of time and distinguish their important decisions.

Effective risk management that is based on a principle/concept forms an important part of the decision-making process in the S-SCM. In this section, the principles are focused by identifying the core elements of risks and by investigating the potential impacts in the success of the organization and by discussing how to handle and manage risks.

The studied company is an outstanding far-reaching manufacturing service provider that recommends engineering tests, package design, integrated circuit (IC) assembly, final test, and design manufacturing services. By considering these manufacturing abilities, the case company can furnish its clients with final semiconductor turnkey arrangements. The fundamental business administrations of the case organization are IC and framework administrations. Keeping in mind the end goal to give fast services to global clients, the case organization's backups are based close to their abroad clients in Asia, Americas, and Europe. The studied company additionally puts resources into equipment and facilities to regard its client' demands [8].

The company's principle raw materials are lead frames, IC substrates, molding compounds, and gold wires. Raw material costs represent roughly half of the final manufacturing cost of the case organization. With the exception of the molding compounds, the cost of the other raw materials is firmly identified with the cost of the mechanical and valuable metals. Due to much higher manufacturing cost, the case incurred a high loss of profit. Moreover, the most of the case organization's providers are in foreign countries. In this way, the case confronts some supply chain risks in securing the raw materials. The studied company faces some supply chain risks in securing its raw materials. For instance, it can have trouble filling its urgent requests via air and with its items' cost and quality. Hence, in this organization, selecting the suitable supplier candidates is regarded as the critical choice issue. In Fig. 5, a hierarchical structure of the FMEA-decision problem is presented for the real application.

In the organization, 17 supplier candidates' risks (R_i) are regarded for the planning, and a group of three experts from the organization (TM_k) are established for the selection problem. TM_1 is optimistic, and TM_2 and TM_3 are pessimistic. Three principle assessment criteria of the FMEA, including O, S, and D, are regarded for the group decision making for the supplier selection problem. The risks of supplier candidates as alternatives (R_i; $i = 1, 2, \ldots, 17$) in six categories, including cost, quality, deliverability, technology, productivity, and service, in the decision matrixes are as follows:

- Product's total cost risk (R_1)
- Cost reduction plan risk (R_2)
- Input quality control risk (R_3)
- Manufacturing capability risk (R_4)
- Reliability risk (R_5)
- High yield control risk (R_6)
- Production cycle risk (R_7)
- On time delivery risk (R_8)
- Delivery lead time risk (R_9)
- Design capability risk (R_{10})
- Problem solving capability risk (R_{11})
- Continuous improvement capability risk (R_{12})
- Productivity flexibility risk (R_{13})
- Amount of production risk (R_{14})
- Complaint processing risk (R_{15})
- Response to demands risk (R_{16})
- Report generation risk (R_{17})

For three dimensions of the sustainability, these risks are regarded as economics dimension including R_1, R_2, R_4, R_5, R_7, R_8, R_{14}, R_{16}, social dimension including R_3, R_6, R_{11}, R_{12}, R_{15}, and environmental dimension including R_{10}, R_{13}, R_{17}.

In this case study for the evaluation and selection problem of the suppliers, linguistic variables are taken for the performance ratings of the supplier candidates' risks by using Table 3. Then, the evaluation results about the weights and ratings that are transformed into IVFNs are provided for suppliers A, B, and C. Then, the IVF-decision matrices of supplier candidates' risks are provided by each supply chain-decision maker and then are aggregated by Eq. (6).

The aggregated IVF-matrixes are transformed into normalized matrix of supplier candidates' risks. Then, the possibilistic interval mean, standard deviation, and cube-root of skewness matrixes for the supplier selection problem are constructed. The possibilistic interval mean-entropy measure

Table 4 Computational results for supplier A in the case study

Risks	$\frac{(\underline{S}_i^M)^+ + (\underline{S}_i^{SD})^+ + (\underline{S}_i^{CRS})^+}{3}$	$\frac{(\bar{S}_i^M)^+ + (\bar{S}_i^{SD})^+ + (\bar{S}_i^{CRS})^+}{3}$	$\frac{(\underline{R}_i^M)^+ + (\underline{R}_i^{SD})^+ + (\underline{R}_i^{CRS})^+}{3}$	$\frac{(\bar{R}_i^M)^+ + (\bar{R}_i^{SD})^+ + (\bar{R}_i^{CRS})^+}{3}$	$\frac{(\underline{S}_i^M)^- + (\underline{S}_i^{SD})^- + (\underline{S}_i^{CRS})^-}{3}$	$\frac{(\bar{S}_i^M)^- + (\bar{S}_i^{SD})^- + (\bar{S}_i^{CRS})^-}{3}$	$\frac{(\underline{R}_i^M)^- + (\underline{R}_i^{SD})^- + (\underline{R}_i^{CRS})^-}{3}$	$\frac{(\bar{R}_i^M)^- + (\bar{R}_i^{SD})^- + (\bar{R}_i^{CRS})^-}{3}$
(R_1)	1.362	1.871	1.070	1.469	1.269	1.772	1.015	1.397
(R_2)	1.224	1.541	1.122	1.326	1.149	1.466	1.032	1.220
(R_3)	1.136	1.448	1.033	1.221	1.174	1.480	1.056	1.249
(R_4)	0.977	1.249	0.874	1.034	0.893	1.163	0.775	0.917
(R_5)	1.300	1.641	1.173	1.386	1.040	1.324	0.954	1.128
(R_6)	1.224	1.541	1.122	1.326	1.149	1.466	1.032	1.220
(R_7)	1.191	1.524	1.063	1.262	1.085	1.362	0.999	1.181
(R_8)	0.977	1.249	0.874	1.034	0.893	1.163	0.775	0.917
(R_9)	1.330	1.666	1.229	1.453	1.210	1.543	1.084	1.289
(R_{10})	0.975	1.245	0.874	1.034	0.902	1.183	0.775	0.917
(R_{11})	1.281	1.631	1.154	1.364	1.221	1.523	1.135	1.342
(R_{12})	1.224	1.553	1.122	1.326	1.149	1.452	1.032	1.220
(R_{13})	1.302	1.645	1.173	1.386	1.106	1.431	0.956	1.141
(R_{14})	1.002	1.301	0.874	1.034	0.862	1.098	0.775	0.917
(R_{15})	1.224	1.541	1.122	1.326	1.149	1.466	1.032	1.220
(R_{16})	0.977	1.249	0.874	1.034	0.893	1.163	0.775	0.917
(R_{17})	1.256	1.592	1.154	1.364	1.252	1.605	1.135	1.342

Table 5 Computational results for supplier B in the case study

Risks	$\frac{(\underline{S}_i^M)^+ + (\underline{S}_i^{SD})^+ + (\underline{S}_i^{CRS})^+}{3}$	$\frac{(\bar{S}_i^M)^+ + (\bar{S}_i^{SD})^+ + (\bar{S}_i^{CRS})^+}{3}$	$\frac{(\underline{R}_i^M)^+ + (\underline{R}_i^{SD})^+ + (\underline{R}_i^{CRS})^+}{3}$	$\frac{(\bar{R}_i^M)^+ + (\bar{R}_i^{SD})^+ + (\bar{R}_i^{CRS})^+}{3}$	$\frac{(\underline{S}_i^M)^- + (\underline{S}_i^{SD})^- + (\underline{S}_i^{CRS})^-}{3}$	$\frac{(\bar{S}_i^M)^- + (\bar{S}_i^{SD})^- + (\bar{S}_i^{CRS})^-}{3}$	$\frac{(\underline{R}_i^M)^- + (\underline{R}_i^{SD})^- + (\underline{R}_i^{CRS})^-}{3}$	$\frac{(\bar{R}_i^M)^- + (\bar{R}_i^{SD})^- + (\bar{R}_i^{CRS})^-}{3}$
(R_1)	1.292	2.281	0.839	1.404	1.569	2.693	1.006	1.617
(R_2)	0.867	1.451	0.649	0.769	1.071	1.692	0.845	1.001
(R_3)	1.292	2.281	0.839	1.404	1.569	2.693	1.006	1.617
(R_4)	1.252	2.176	0.868	1.356	0.810	1.633	0.737	1.240
(R_5)	1.248	2.196	0.787	1.309	1.426	2.423	0.924	1.462
(R_6)	1.292	2.281	0.839	1.404	1.569	2.693	1.006	1.617
(R_7)	1.292	2.255	0.839	1.404	1.569	2.631	1.006	1.617
(R_8)	1.248	2.013	0.787	1.309	1.426	2.197	0.924	1.462
(R_9)	1.292	2.281	0.839	1.404	1.569	2.693	1.006	1.617
(R_{10})	1.252	2.018	0.868	1.356	0.810	1.468	0.737	1.248
(R_{11})	1.292	2.255	0.839	1.404	1.569	2.631	1.006	1.617
(R_{12})	0.871	1.306	0.653	0.774	0.456	0.811	0.361	0.539
(R_{13})	1.248	2.013	0.787	1.309	1.426	2.197	0.924	1.462
(R_{14})	0.867	1.477	0.649	0.769	1.071	1.754	0.845	1.001
(R_{15})	0.867	1.293	0.649	0.769	1.071	1.528	0.845	1.001
(R_{16})	1.297	2.260	0.955	1.522	0.953	1.903	0.849	1.462
(R_{17})	1.292	2.255	0.839	1.404	1.569	2.631	1.006	1.617

Table 6 Computational results for supplier C in the case study

Risks	$\frac{(\underline{S}_i^M)^+ + (\underline{S}_i^{SD})^+ + (\underline{S}_i^{CRS})^+}{3}$	$\frac{(S_i^M)^+ + (S_i^{SD})^+ + (S_i^{CRS})^+}{3}$	$\frac{(\underline{R}_i^M)^+ + (\underline{R}_i^{SD})^+ + (\underline{R}_i^{CRS})^+}{3}$	$\frac{(R_i^M)^+ + (R_i^{SD})^+ + (R_i^{CRS})^+}{3}$	$\frac{(\underline{S}_i^M)^- + (\underline{S}_i^{SD})^- + (\underline{S}_i^{CRS})^-}{3}$	$\frac{(S_i^M)^- + (S_i^{SD})^- + (S_i^{CRS})^-}{3}$	$\frac{(\underline{R}_i^M)^- + (\underline{R}_i^{SD})^- + (\underline{R}_i^{CRS})^-}{3}$	$\frac{(R_i^M)^- + (R_i^{SD})^- + (R_i^{CRS})^-}{3}$
(R_1)	0.836	1.057	0.780	0.850	0.549	0.704	0.506	0.552
(R_2)	0.863	1.069	0.806	0.879	0.920	1.129	0.877	0.955
(R_3)	0.819	1.012	0.771	0.840	0.973	1.196	0.921	1.004
(R_4)	0.863	1.069	0.806	0.879	0.920	1.129	0.877	0.955
(R_5)	0.836	1.038	0.780	0.850	0.549	0.732	0.506	0.561
(R_6)	0.489	0.662	0.448	0.510	0.412	0.576	0.369	0.430
(R_7)	0.863	1.069	0.806	0.879	0.920	1.129	0.877	0.955
(R_8)	0.828	1.048	0.771	0.840	0.965	1.156	0.921	1.004
(R_9)	0.863	1.069	0.806	0.879	0.920	1.129	0.877	0.955
(R_{10})	0.483	0.647	0.433	0.472	0.429	0.618	0.369	0.433
(R_{11})	0.857	1.054	0.806	0.879	0.937	1.172	0.877	0.955
(R_{12})	0.827	1.021	0.780	0.850	0.558	0.743	0.515	0.572
(R_{13})	0.480	0.661	0.438	0.488	0.421	0.618	0.369	0.450
(R_{14})	0.828	1.030	0.771	0.840	0.965	1.178	0.921	1.004
(R_{15})	0.863	1.069	0.806	0.879	0.920	1.129	0.877	0.955
(R_{16})	0.836	1.040	0.780	0.850	0.549	0.725	0.506	0.554
(R_{17})	0.828	1.030	0.771	0.840	0.965	1.178	0.921	1.004

of each evaluation criterion is computed by using Eqs. (15) and (16). Then, the weights of these three evaluation criteria of 17 risks are provided according to steps 7 and 8 for suppliers A, B, and C as below:

Supplier A: $W_1 = \{(0.0000,0.0373), (0.0761,0.1230), (0.5008,0.5921)\}$;
Supplier B: $W_2 = \{(0.0000,0.1060), (0.2219,0.4193), (0.7157,0.8478)\}$;

and

Supplier C: $W_3 = \{(0.0000,0.0546), (0.0658,0.1382), (0.5803,0.6323)\}$

Positive-ideal and negative-ideal vectors (PIV and NIV) of possibilistic interval mean, and PIV and NIV of possibilistic interval standard deviation as well as the PIV and NIV of possibilistic interval cube-root of skewness are defined for the selection problem. Consequently, the separation measures of each supplier candidate's risks of possibilistic interval mean, standard deviation, and cube-root of skewness from the PIV ($\bar{M}^*$, $\bar{Sd}^*$, and $\bar{Crs}^*$) and from the NIV ($\bar{M}^-$, $\bar{Sd}^-$, and $\bar{Crs}^-$) are calculated, respectively. Finally, novel separation measures are computed using Euclidean distance for the selection problem. The computational results of proposed max-and min-indices and final values of T_i with $\varphi = 0.5$ for three supplier candidates are reported in Tables 4, 5, 6, 7.

The results of proposed FMEA procedure based on new IVF-group decision-making approach with possibilistic interval mean, possibilistic interval standard deviation, and possibilistic interval cube-root of skewness have been compared with the approach of Chen and Wu [8] based on AHP method and reported in Table 7. Comparing the proposed model with AHP method shows that the most suitable and the worst candidate suppliers are supplier B and supplier C, respectively.

In addition, a sensitivity analysis is presented about weights of the strategy of the majority of criteria. ν and μ in Eqs. (49) and (50) within the range of 0 to 1, for I_i and P_i values of each supplier risk ($i = 1, 2, \ldots, 17$), are regarded; the computational results are reported in Table 8. Also, $\nu = \mu = 0.5$ as main condition is provided for the selection problem. The results indicate that changing on weights of the strategy of the majority of criteria cannot effect on the final ranking of the proposed FMEA approach for the selection problem.

6 Comparative analysis and managerial implications

In this section, a comparative analysis is provided for the proposed new FMEA approach and the approach by Chen and Wu [8] based on the AHP method on the case study in

Table 7 Proposed indices' values and supplier ranking by the proposed FMEA model for the case study

Indices	Supplier (A)	Supplier (B)	Supplier (C)
χ^*	0.975	0.867	0.483
χ^-	1.871	2.281	1.069
ϑ^*	0.862	0.649	0.433
ϑ^-	1.469	1.522	0.879
ψ^*	1.772	2.693	1.196
ψ^-	0.893	0.456	0.412
δ^*	1.397	1.617	1.004
δ^-	0.775	0.361	0.369
T_i	21.10	18.76	25.64
Supplier ranking	2	1	3
Average RPNs of six criteria by Chen and Wu [8]	1.03	0.62	1.13
Supplier ranking by Chen and Wu [8]	2	1	3

the manufacturing services. The comparative analysis based on some important comparison parameters, according to the recent literature (e.g. [20, 35]), are presented in detail as follows:

6.1 Agility in decision process

This comparison parameter evaluates the amount of required preference judgments of supply chain-experts that are provided by the DMs in both the proposed FMEA approach and proposed AHP method by Chen and Wu [8]. Let m the number of alternatives, n the number of criteria, and k the number of the supply chain-experts. The fuzzy FMEA approach requires mnk judgments to build the decision matrix by a group of experts. However, in the AHP method by Chen and Wu [8], it can be observed that as the number of evaluation criteria and supplier alternatives increases, in general, the number of required supply chain-experts' judgments by the AHP in comparison with using the proposed FMEA approach increases.

6.2 Influence of supply chain-experts' opinions with asymmetric uncertainty information

Opinions of the supply chain-experts with asymmetric uncertainty information (i.e., optimistic and pessimistic attitudes) might be different in the industry based on different experiences and characteristics; hence, considering the opinions of the supply chain-experts with asymmetric uncertainty information could help the supply chain-DMs to achieve a precise solution. In this application, the opinions of supply chain-experts are not regarded as neutral; then, the ranking order results are supplier A > supplier B > supplier C, which is somewhat different from the ranking order results of each of supply chain-experts. However, this issue is not taken into account in the AHP method by Chen and Wu [8]. The comparative analysis based on this comparison parameter indicates that the final ranking order of three supplier candidates is affected from the opinions of three experts with asymmetric uncertainty information. It is obvious that considering the opinions with asymmetric uncertainty information could lead to an accurate result of the selection problem.

6.3 Modeling of uncertainty

Proposed FMEA approach employs interval-valued fuzzy sets theory to handle the inherent lack of precision of the data regarded in the selection and evaluation problem in the manufacturing services, unlike the proposed AHP method by Chen and Wu [8] as deterministic approach. In the proposed FMEA approach, the interval-valued fuzzy number is the main resource for quantifying imprecision. Due to the vagueness of three supply chain-experts' judgments for qualitative variables, the parameters of the interval-valued triangular fuzzy membership functions can be determined so as to better express the linguistic terms provided by each supply

Table 8 Sensitivity analysis of the proposed model for the case study

Supplier candidate	$v=\mu=0$	$v=\mu=0.1$	$v=\mu=0.2$	$v=\mu=0.3$	$v=\mu=0.4$	$v=\mu=0.5$ Main condition	$v=\mu=0.6$	$v=\mu=0.7$	$v=\mu=0.8$	$v=\mu=0.9$	$v=\mu=1$
$T_{(A)}$	23.93	23.19	22.55	22.00	21.52	21.10	20.73	20.41	20.14	19.90	19.69
$T_{(B)}$	18.32	18.39	18.47	18.56	18.56	18.65	18.76	19.01	19.15	19.31	19.49
$T_{(C)}$	34.47	31.90	29.75	28.11	26.76	25.64	24.69	23.87	23.15	22.52	21.96

chain-expert to assess the supplier alternatives versus different evaluation criteria.

6.4 Adequacy to changes of supplier alternatives or evaluation criteria

One of main comparison parameters is adequacy to changes of supplier alternatives or evaluation criteria in the selection process that could provide ranking reversal in the ordering of potential supplier alternatives or evaluation criteria. The adding or excluding one supplier alternative is assessed by both the proposed FMEA approach and the AHP method by Chen and Wu [8]; the same ranking results are reported. The ranking order of the supplier alternatives in the case study for the manufacturing services by adding/excluding the supplier alternatives is achieved as: supplier B > supplier A > supplier C. In addition, the computational results are determined for adding/excluding the evaluation criteria; it means that the importance order has no changes. However, in the method by Chen and Wu [8], when the additional evaluation criterion has a weight equal to the one of the three criteria, there is an inversion of the importance order. It denotes that the ranking reversal may be occurred by changing of evaluation criteria. Nevertheless, in the proposed FMEA approach, adding a new evaluation criterion has reported no change to the importance order of evaluation criteria.

6.5 Managerial implications

The implementation of the presented new FMEA approach in real-life application of the selection problem in the manufacturing services provides some significant issues as follows:

- The proposed FMEA approach concurrently utilizes IVFSs and mean-variance-skewness concepts by a group of supply chain-experts to solve this selection problem. The uncertain modeling makes the FMEA approach more practical. Indeed, in the real-life application of the manufacturing services, the performance values of the supplier candidates have been determined by interval-valued fuzzy numbers, and consequently describing lack of information, risks, and uncertainties was easier by considering the optimistic and pessimistic preferences of the supply chain-experts. Finally, the outcomes have demonstrated the effects of vulnerability on the supplier selection problems.
- The proposed FMEA approach is based on new definitions for obtaining positive and negative-ideal solutions with values of possibilisic mean, possibilistic standard deviation, and the cube-root of skewness under the interval-valued fuzzy environment. The definitions not only make the proposed FMEA approach more realistic but also make closer to what supply chain-experts present in real-life applications in the manufacturing services.
- Introducing new max- and min-indices as well as new scoring index of closeness coefficients provide the supply chain-experts with more capability in distinguishing all supplier alternatives with the interval-valued fuzzy setting in the S-SCM.
- Fuzzy possibilitic statistical approach, asymmetric uncertainty information, and interval-valued fuzzy setting by a group of supply chain-experts have not been taken into account simultaneously in the literature of supplier selection and evaluation to select the most suitable supplier from a number of potential alternatives. Moreover, extending a possibilistic interval mean-entropy measure for computing the weight of each evaluation factor with asymmetric uncertainty information provides more information for the final supplier selection and assessment. The proposed integrated mean-variance-skewness model can deal with higher level of risks and uncertainties in the real-life applications of supplier selection problems, and can present higher performance unlike the previous studies.

7 Conclusions

Supply chain risk is an important issue in today's business environment. As companies increase their activities and scopes to incorporate global operations, supply chain management turns into an undeniably critical function by considering sustainable development concepts. FMEA is an effective reliability evaluation model that can be applied to recognize and assess potential failures in systems, products, processes, and/or designs in the supply chain. In conventional FMEA, ranking of failure modes is completed by using RPNs, which can be procured by the multiplication of three main risk factors, including occurrence (O), severity (S), and detection (D). In many applications, there are some insufficiencies in the traditional RPN that can influence its effectiveness. This paper introduced a new FMEA procedure of evaluating a suitable supplier in the S-SCM under uncertain conditions. The proposed FMEA was based a new interval-valued fuzzy decision-making approach with the possibilistic statistical concepts. For this purpose, a new FMEA process for group decision-making with asymmetric uncertainty information was presented under the interval-valued fuzzy environment. The evaluation was based on compromise programming concepts and two possibilistic mean, standard deviation, and cube-root of skewness matrices. For computing the weights of three main risk factors, a new possibilistic interval mean-entropy method was extended. Finally, several min- and max-evaluation indices and a new ranking index were proposed to obtain the risks scores of all sustainable-supplier candidates with interval-valued fuzzy setting. The proposed FMEA procedure enhanced levels of the analysis quality based on a fuzzy possibilistic statistical approach. Consequently, a case study from the recent literature was provided for the supplier problems to evaluate the sustainable-supply chain risks under uncertain conditions. In addition, a comparative analysis was provided with the AHP method for the supplier evaluation problem. For further research, the proposed FMEA model can be extended to interval type-2 fuzzy sets and possibilistic concepts. Also, the proposed model can be improved through the group decision-making process by exploring the potential of using the last aggregation approach and different weights of sustainable-supply chain-experts. In this regard, a new weighting method based on the compromise solution for each sustainable-supply chain-DM or expert can be presented with interval-valued fuzzy sets and the possibilistic statistical concepts. In addition, the proposed procedure can be extended for solving complex decision-making problems where the information about criteria' weights is incomplete under uncertainty.

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