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METHODOLOGIES AND APPLICATION

A modified failure modes and effects analysis using interval-valued spherical fuzzy extension of TOPSIS method: case study in a marble manufacturing facility

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Abstract

Failure modes and effects analysis (FMEA) is a commonly used step-by-step approach to assess potential failures existing in a product or process design. In this paper, a modified FMEA model based on an interval-valued spherical fuzzy extension of technique for order preference by similarity to ideal solution (IVSF-TOPSIS) is proposed to cope with drawbacks of the traditional risk priority number (RPN) computation. Spherical fuzzy sets are the integration of Pythagorean fuzzy sets and neutrosophic sets. They provide more freedom to experts in decision making by including the degree of membership, non-membership, and hesitation of fuzzy sets. Therefore, initially, TOPSIS is merged with a special branch of spherical sets "interval-valued spherical fuzzy sets" to determine priorities of emerged failures. As a novelty to traditional RPN of FMEA, three parameters called cost, prevention, and effectiveness in addition to the existed parameters of severity, occurrence and detection are attached to the proposed approach. Weights of these parameters are determined via an interval-valued spherical weighted arithmetic mean operator (IVSWAM). As a demonstration, a case study in a marble manufacturing facility is provided to show the applicability of the novel model. Results show that the most crucial failure modes concern with the maintenance and repairing works of the factory and the lack of technical periodic checks of lifting vehicles regarding "block area: crane" failures. Some comparative and validation studies are also performed to test the solidity of the approach.

Keywords FMEA · Interval-valued spherical fuzzy sets · TOPSIS · Marble manufacturing

1 Introduction

Failure modes and effects analysis (FMEA) is a systematic approach used in assessing potential failures during designing a product or process (Ozdemir et al. 2017). Since it has been proposed for the aerospace industry for the first time, it has recently been applied to diverse problems in various areas (Liu et al. 2013, 2019). Considering the application domain specialty and scope, there exist different types of FMEA in the literature, such as system FMEA, design FMEA, process FMEA, service FMEA, software FMEA, and manufacturing FMEA. The initially proposed version of FMEA has three parameters, named severity (S), occurrence (O), and detection (D) to open to a risk priority number (RPN). This value is calculated by multiplying these three parameters together. Each parameter takes values as 1 lowest and 10 highest. The scale of 1 shows "none" in severity, "extremely remote" in occurrence and "almost certain" in detection; the scale of 10 points "hazardous without warning" in severity, "extremely high" in occurrence and "absolutely uncertainty" in detection (Bozdag et al. 2015). Failure modes with high RPN are more crucial and are ranked prior to those with low RPN (Park et al. 2018). Then, the required control measures should be taken in accordance with the obtained priorities of failure modes. Although this classical RPN

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logic seems a systematic way to rank failures in system safety assessment, it has many disadvantages handled before in the literature (Başhan et al. 2020; Qin et al. 2020; Bhattacharjee et al. 2020; Wang et al. 2020; Rezaee et al. 2020; Baykasoğlu and Gölcük, 2020; Fattahi et al. 2020; Lo et al. 2020; Gul et al. 2020; Yucesan and Gul, 2019; Di Bona et al. 2018; Ozdemir et al. 2017; Liu et al. 2019; 2013; Bozdag et al. 2015; Park et al. 2018; Liu, 2016). Some of those include as follows:

- Apart from these three parameters (S, O, and D), additional parameters that have an impact on risk assessment have not been taken into account (Liu et al. 2019; Di Bona et al. 2018). Therefore, parameters such as economic loss (e.g., total cost or external costs), prevention, sensitivity to non-usage of personal protective equipment, sensitivity to non-execution of reactive and proactive maintenance, effectiveness of prevention measures and strategies should be taken into account in new and novel FMEA extended studies (Seiti et al. 2020; Du et al. 2016; Lo et al. 2019).
- Weights of S, O, and D are not considered in RPN computation in the traditional FMEA (Park et al. 2018; Liu et al. 2013; Huang et al. 2017).
- Different ratings of S, O, and D may result in the same RPN. However, their risk priorities are absolutely different (Huang et al. 2017; Catelani et al. 2018; Du et al. 2016; Safari et al. 2016).
- The S, O, and D parameters are not easy to be precisely examined due to their subjective evaluation on a 1–10-scale basis. The use of linguistic terms in fuzzy numbers can better drive the FMEA (Zhang et al. 2020; Mete 2019; Gul and Ak 2020; Ozdemir et al. 2017; Zhao et al. 2017; Lo et al. 2019; Kutlu and Ekmekçioğlu 2012). More shortcomings can be found in Liu et al. (2013) and Liu et al. (2019), which cover two important literature reviews of FMEA-based studies.

In this study, a modified FMEA model based on interval-valued spherical fuzzy extension of technique for order preference by similarity to ideal solution (IVSF-TOPSIS) is proposed to cope with limitations of the traditional RPN assessment style.

Elements of fuzzy set have degrees of membership. Fuzzy sets were first introduced by Lotfi A. Zadeh as an extension of the classical notion of set and applied to various areas from manufacturing to service systems (Reddy and Khare 2017a; b). Over years, many extensions are proposed to improve this type of sets. One of them is spherical fuzzy documentation. Spherical fuzzy sets proposed by Kutlu Gündoğdu and Kahraman (2019a) reflect uncertainty and ambiguity in real-world decision problems better than classical fuzzy set theory. They are mathematically based on a membership function on a spherical surface. They independently describe degree of membership, non-membership and hesitancy in a larger domain (the sum of these three values must be between 0 and 1). They are considered as the integration of Pythagorean fuzzy sets and neutrosophic sets. They eliminate some aspects of neutrosophic sets and Pythagorean fuzzy sets as follows (Kutlu Gündoğdu and Kahraman 2019a; b; Balin 2020):

- They cannot permit the sum of membership, non-membership and hesitancy degrees to be larger than 1 and,
- They do not disregard an independent hesitancy unlike Pythagorean fuzzy sets.

In this study, a special branch of spherical sets "interval-valued spherical fuzzy sets" is used with a multi-criteria decision-making (MCDM) method of TOPSIS. Interval-valued fuzzy sets provide decision maker to model their decision-making problem via an interval fuzzy framework instead of a single point. By this aspect, it helps decision makers to clarify their judgments more accurately. Initially, TOPSIS is merged with interval-valued spherical fuzzy sets to determine priorities of emerged failures. As a novelty to classical RPN of FMEA, three parameters called cost, prevention, and effectiveness in addition to the existed parameters of severity, occurrence, and detection are attached to the proposed approach. Weights of these parameters are determined via a spherical fuzzy arithmetic mean operator. Adding three more parameters to traditional FMEA and weighting these parameters eliminate the above-mentioned shortcomings of traditional FMEA. In addition, integration with IVSF-TOPSIS reveals the originality of the current study. TOPSIS is a widely used MCDM method developed by Yoon and Hwang (1981). It represents the MCDM problem aiming at finding the best alternative considering the distances from the positive and the negative ideal solution.

In the FMEA literature, several improvements have been gained from both methodological and application point of view. Specifically, the fuzzy set-related improvements are forefront. Recent extensions of fuzzy sets have been integrated into the concept of traditional FMEA such as triangular fuzzy sets, trapezoidal fuzzy sets, intuitionistic fuzzy sets, interval type-2 fuzzy sets, hesitant fuzzy sets, Pythagorean fuzzy sets, and spherical fuzzy sets to eliminate its drawbacks and improve the base version. MCDM-based, belief rules-based and some miscellaneous methodologies are also the most preferred FMEA improvement.

Li et al. (2019) proposed an integrated rough set and TOPSIS. They benefited from the advantage of rough set theory by providing the cloud model. Park et al. (2018) proposed "importance RPN" considering a three-dimensional geometric approach. Guo et al. (2018) proposed a hesitant fuzzy VIKOR (vlsekriterijumska optimizacija i kompromisno resenje)-based approach for FMEA for carbon dioxide transfer pipelines. In the approach, three parameters of FMEA were weighted by maximizing deviation method and fuzzy analytic hierarchy process (FAHP). Then, failure modes were prioritized by hesitant fuzzy VIKOR. Bian et al. (2018) developed a new risk assessment model based on the integration of D numbers and TOPSIS. Hu et al. (2018) integrated uncertain linguistic grey relation analysis (GRA) and TOPSIS for a healthcare risk analysis problem. Huang et al. (2018) proposed a model to evaluate multiple experts' opinions in risk analysis using fuzzy numbers and Dempster–Shafer (D–S) evidence theory. Fattahi and Khalilzadeh (2018) presented an FMEA-based risk assessment by integrating multiple multi-objective optimizations by ratio analysis (MULTIMOORA) and fuzzy AHP methods. Carpitella et al. (2018) developed a new version of FMEA using AHP and fuzzy TOPSIS methods. Time of operation, a modality of execution, and frequency of occurrence were the revised parameters of FMEA and were weighted by AHP. Then, fuzzy TOPSIS was applied to rank previously identified failure modes. Akyuz and Celik (2018) performed a risk-based approach merging interval type-2 fuzzy sets with FMEA. Lo and Liou (2018) proposed an MCDM model in combination with a grey theory for FMEA. An additional risk parameter called "cost" was also used in their study. Risk parameters' weights were determined best-worst method (BWM). Another study by Tian et al. (2018) applied an extended version of BWM with fuzzy sets, relative entropy, and fuzzy VIKOR methods in FMEA risk assessment. Jiang et al. (2017) proposed an FMEA model based on a novel fuzzy evidential method. There exist methods applied intuitionistic (Tooranloo and Ayatollah 2016) and interval type-2 fuzzy sets (Chai et al. 2016) with MCDM in FMEA-based risk assessment. For instance, Tooranloo and Ayatollah (2016) proposed a novel model for FMEA based on an intuitionistic fuzzy approach. Chai et al. (2016) developed a perceptual computing-based method to prioritize failure modes in FMEA using interval type-2 fuzzy sets. Since the risk parameters and associated failure modes are better evaluated by fuzzy numbers, most of the above-mentioned recent FMEA studies have applied fuzzy set theory and its different versions. Each has improved the drawbacks of traditional FMEA procedure and solved the issues in terms of reflecting uncertainty and vagueness. But sometimes, it becomes difficult to reflect and characterize the decision-making situation in FMEA by all aspects using the above-mentioned fuzzy set extensions. For such cases, spherical fuzzy sets are more suitable to apply within FMEA.

From an application point of view, a limited number of papers are released in the literature to improve the occupational health and safety (OHS) process of marble production (Rezaee et al. 2017; Ersoy et al. 2017; Özfırat et al. 2017; Ersoy 2015). In Ersoy (2015), a method called failure-consequence analysis is used. Ersoy et al. (2017) proposed an FMEA (its base version) method. Similarly, Özfırat et al. (2017) applied a traditional 5 × 5 matrix method (L-matrix). Although there are very few FMEA-based risk assessment studies in the marble production industry (Rezaee et al. 2017; Ersoy 2015), an improved and novel approach with fewer disadvantages is required for the risk assessment process of marble production. The current FMEA based on IVSF-TOPSIS study will be to remedy this gap.

The main contributions of the paper are provided in the following:

- IVSFSs are used in the proposed holistic FMEA study. This type of fuzzy sets eliminates some missing aspects of neutrosophic sets and Pythagorean fuzzy sets by not permitting the sum of membership, non-membership, and hesitancy degrees to be larger than 1 and, not disregarding an independent hesitancy, unlike Pythagorean fuzzy sets.

- IVSF-TOPSIS jointly used with the concept of FMEA is applied to prioritize the failure modes with respect to increased FMEA parameters in number.
- Three additional parameters called cost, prevention, and effectiveness are attached to the study.
- Interval-valued spherical weighted arithmetic mean (IVSWAM) operator is used to determine the importance weights of six FMEA parameters before failure mode prioritization.
- A real case study concerning failure modes and effects analysis in the marble production industry is carried out to show the applicability of the novel model.
- A broader comparison and a sensitivity analysis are also performed to validate the model.

The organization of the remaining sections of this study is as follows: Some basic preliminaries on IVSFSs, the procedure of IVSF-TOPSIS and novel holistic FMEA model are described in Sect. 2. In Sect. 3, application of the proposed approach to a real case study in marble industry is given. The results, discussion, comparative and sensitivity analysis are demonstrated in Sect. 4. Final section includes the conclusion and future work opportunities.

2 Methodology

In this section, preliminaries of spherical fuzzy sets and interval-valued spherical fuzzy sets are introduced. Then, procedural steps of IVSF-TOPSIS are presented with its descriptive formulations.

2.1 Preliminaries on spherical fuzzy sets

Spherical fuzzy sets are integration of Pythagorean fuzzy sets and neutrosophic sets. In intuitionistic and Pythagorean fuzzy sets, the relation between three membership degrees named as membership, non-membership and hesitancy is formed, respectively, as in Eqs. (1, 2) (Kutlu Gundogdu and Kahraman 2019a, b; Shishavan et al. 2020):

$$0 \le \mu_I(x) + v_I(x) \le 1 \text{ and } \pi_I(x) = 1 - \mu_I(x) - v_I(x) \quad (1)$$

$$0 \le \mu_P(x)^2 + v_P(x)^2 \le 1 \text{ and } \pi_P(x) = \sqrt{1 - \mu_P^2(x) - v_P^2(x)} \quad (2)$$

Membership functions in neutrosophic sets are also defined under three pillars called as truthiness membership, falsity membership and indeterminacy membership. Sum of these three membership values can be between 0 and 3.

In spherical fuzzy sets, while the squared sum of three parameters can be between 0 and 1, each of them can be defined between 0 and 1 independently. For graphical representation of these sets, one can refer to Kutlu Gundogdu and Kahraman (2019a).

Spherical fuzzy sets are applied in multi-criteria problems (Ullah et al. 2020; Yang et al. 2020; Perveen et al. 2019; Zeng et al. 2019; Garg et al. 2018) and combined with frequently used MCDM methods although it has been recently emerged (Ozceylan et al. 2020). AHP (Gündoğdu and Kahraman 2020a), TOPSIS (Kutlu Gundogdu and Kahraman, 2019a; 2019b; Kahraman et al. 2019), VIKOR (Kutlu Gündoğdu and Kahraman 2019c; Gündoğdu et al. 2019), weighted aggregated sum product assessment (WASPAS) (Kutlu Gündoğdu and Kahraman 2019d), quality function deployment (QFD) (Gündoğdu and Kahraman 2020b), MULTIMOORA (Kutlu Gündoğdu, 2020), combine distance-based assessment (CODAS) (Karaşan et al. 2020) and decision-making trial and evaluation laboratory (DEMATEL) (Gül, 2020) are MCDM methods extended with Spherical fuzzy sets. Gündoğdu and Kahraman (2020a, b) developed a novel spherical FAHP and applied it to renewable energy location selection. Kutlu Gündoğdu and Kahraman (2019c) proposed a spherical fuzzy VIKOR and applied it for warehouse site selection. In another study, Kutlu Gündoğdu and Kahraman (2019d) extended WASPAS method with spherical fuzzy sets and applied the extended method in industrial robot selection problem.

Some mathematical operations in spherical fuzzy numbers are provided as follows by Eqs. (3–6) (Kutlu Gundogdu and Kahraman 2019a, b; Shishavan et al. 2020):

Let $\tilde{S}_1$ and $\tilde{S}_2$ two different spherical fuzzy numbers of the universe of discourse U.

$$\tilde{S}_1 = \left\{ u, (\mu_{\tilde{S}_1}(u), v_{\tilde{S}_1}(u), \pi_{\tilde{S}_1}(u)) | u \epsilon U \right\} \text{ and}$$

$$\tilde{S}_2 = \left\{ u, (\mu_{\tilde{S}_2}(u), v_{\tilde{S}_2}(u), \pi_{\tilde{S}_2}(u)) | u \epsilon U \right\}$$

$$\tilde{S}_1 \oplus \tilde{S}_2 = \left\{ \sqrt{\mu_{\tilde{S}_1}^2 + \mu_{\tilde{S}_2}^2 - \mu_{\tilde{S}_1}^2 \mu_{\tilde{S}_2}^2}, v_{\tilde{S}_1} v_{\tilde{S}_1}, \sqrt{\left(1 - \mu_{\tilde{S}_2}^2\right)\pi_{\tilde{S}_1} + \left(1 - \mu_{\tilde{S}_1}^2\right)\pi_{\tilde{S}_2} - \pi_{\tilde{S}_1}^2 \pi_{\tilde{S}_2}^2} \right\} \quad (3)$$

$$\tilde{S}_1 \otimes \tilde{S}_2 = \left\{ \mu_{\tilde{S}_1} \mu_{\tilde{S}_2}, \sqrt{v_{\tilde{S}_1}^2 + v_{\tilde{S}_2}^2 - v_{\tilde{S}_1}^2 v_{\tilde{S}_2}^2}, \sqrt{\left(1 - v_{\tilde{S}_2}^2\right)\pi_{\tilde{S}_1}^2 + \left(1 - \mu_{\tilde{S}_1}^2\right)\pi_{\tilde{S}_2}^2 - \pi_{\tilde{S}_1}^2 \pi_{\tilde{S}_2}^2} \right\} \quad (4)$$

$$\lambda \tilde{S}_1 = \left\{ \sqrt{(1 - \left(1 - \mu_{\tilde{S}_1}^2\right)^{\lambda})}, v_{\tilde{S}_1}^{\lambda}, \sqrt{\left(1 - \mu_{\tilde{S}_1}^2\right)^{\lambda} - \left(1 - \mu_{\tilde{S}_1}^2 - \pi_{\tilde{S}_1}^2\right)^{\lambda}} \right\} \quad (5)$$

$$\tilde{S_1}^{\lambda} = \left\{ \mu_{\tilde{S_1}}^{\lambda}, \sqrt{(1 - \left(1 - v_{\tilde{S_1}}^2\right)^{\lambda})}, \sqrt{\left(1 - v_{\tilde{S_1}}^2\right)^{\lambda} - \left(1 - v_{\tilde{S_1}}^2 - \pi_{\tilde{S_1}}^2\right)^{\lambda}} \right\} \quad (6)$$

Spherical weighted arithmetic mean (SWAM) operator is defined as in Eq. (7) (Kutlu Gundogdu and Kahraman 2019a, b; Shishavan et al. 2020).

$$SWAM_w\left(\tilde{S_1}, \tilde{S_2}, \ldots \tilde{S_n}\right) = w_1\tilde{S_1} + w_2\tilde{S_2} + \ldots w_n\tilde{S_n}$$
$$= \left\{ \sqrt{1 - \prod_{i=1}^{n}\left(1 - \mu_{\tilde{S_i}}^2\right)^{w_i}}, \prod_{i=1}^{n}\left(v_{\tilde{S_i}}^2\right)^{w_i}, \sqrt{\prod_{i=1}^{n}\left(1 - \mu_{\tilde{S_i}}^2\right)^{w_i} - \prod_{i=1}^{n}\left(1 - \mu_{\tilde{S_i}}^2 - \pi_{\tilde{S_1}}^2\right)^{w_i}} \right\} \quad (7)$$

Here, $w_i \epsilon [0, 1]; \sum_{i=1}^{n} w_i = 1$.

Score and accuracy functions in ranking spherical fuzzy numbers are defined as in Eqs. (8, 9) (Kutlu Gundogdu and Kahraman 2019a, b; Shishavan et al. 2020):

$$Score\left(\tilde{S_i}\right) = \left(\mu_{\tilde{S_i}} - \pi_{\tilde{S_i}}\right)^2 - \left(v_{\tilde{S_i}} - \pi_{\tilde{S_i}}\right)^2 \quad (8)$$

$$Accuracy\left(\tilde{S_i}\right) = \mu_{\tilde{S_i}}^2 + v_{\tilde{S_i}}^2 + \pi_{\tilde{S_i}}^2 \quad (9)$$

Here, it should be noted that $\tilde{S_1} < \tilde{S_2}$ if and only if $Score\left(\tilde{S_1}\right) < Score\left(\tilde{S_2}\right)$ or $Score\left(\tilde{S_1}\right) = Score\left(\tilde{S_2}\right)$ and $Accuracy\left(\tilde{S_1}\right) < Accuracy\left(\tilde{S_2}\right)$.

2.2 Interval-valued Spherical fuzzy sets

Interval-valued spherical fuzzy set is a special sub-branch of spherical fuzzy set and an IVSFS $\tilde{S_i}$ of the universe of discourse U is defined as in Eq. (10):

$$\tilde{S_i} = \left\{ u, ([\mu_{\tilde{S_i}}^L(u), \mu_{\tilde{S_i}}^U(u)], [v_{\tilde{S_i}}^L(u), v_{\tilde{S_i}}^U(u)], ([\pi_{\tilde{S_i}}^L(u), \pi_{\tilde{S_i}}^U(u)]) | u \epsilon U \right\} \quad (10)$$

where

$$0 \le \mu_{\tilde{S_i}}^L(u) \le \mu_{\tilde{S_i}}^U(u) \le 1, 0 \le v_{\tilde{S_i}}^L(u) \le v_{\tilde{S_i}}^U(u) \le 1,$$
$$and\, 0 \le \pi_{\tilde{S_i}}^L(u) \le \pi_{\tilde{S_i}}^U(u) \le 1$$

Some mathematical operations with IVSFSs are defined in the following formulas benefiting from Kutlu Gundogdu and Kahraman (2019a):

Let $\tilde{S_1}$ and $\tilde{S_2}$ be two different interval-valued spherical fuzzy numbers of the universe of discourse U in Eqs. (11, 12).

$$\tilde{S_1} = \left\{ u, ([\mu_{\tilde{S_1}}^L(u), \mu_{\tilde{S_1}}^U(u)], [v_{\tilde{S_1}}^L(u), v_{\tilde{S_1}}^U(u)], ([\pi_{\tilde{S_1}}^L(u), \pi_{\tilde{S_1}}^U(u)]) | u \epsilon U \right\} \quad (11)$$

$$\tilde{S_2} = \left\{ u, ([\mu_{\tilde{S_2}}^L(u), \mu_{\tilde{S_2}}^U(u)], [v_{\tilde{S_2}}^L(u), v_{\tilde{S_2}}^U(u)], ([\pi_{\tilde{S_2}}^L(u), \pi_{\tilde{S_2}}^U(u)]) | u \epsilon U \right\} \quad (12)$$

To avoid any complexity in calculation, a leaner formulation is designed as follows: Let $\tilde{S_1} = \langle [k_1, l_1], [m_1, n_1], [p_1, r_1] \rangle$ and $\tilde{S_2} = \langle [k_2, l_2], [m_2, n_2], [p_2, r_2] \rangle$.

$$\tilde{S_1} \oplus \tilde{S_2} = \left\{ \left[\left(\sqrt{(k_1)^2 + (k_2)^2 - (k_1)^2(k_2)^2} \right), \left(\sqrt{(l_1)^2 + (l_2)^2 - (l_1)^2(l_2)^2} \right) \right], [m_1m_2, n_1n_2], \left[\begin{array}{c} \left(\sqrt{\left(1 - (k_2)^2(p_1)^2\right) + \left(1 - (k_1)^2(p_2)^2\right) - (p_1)^2(p_2)^2} \right), \\ \left(\sqrt{\left(1 - (l_2)^2(r)^2\right) + \left(1 - (l_1)^2(r_2)^2\right) - (r_1)^2(r_2)^2} \right) \end{array} \right] \right\} \quad (13)$$

$$\tilde{S_1} \otimes \tilde{S_2} = \left\{ [k_1k_2, l_1l_2], \left[\left(\sqrt{(m_1)^2 + (m_2)^2 - (m_1)^2(m_2)^2} \right), \left(\sqrt{(n_1)^2 + (n_2)^2 - (n_1)^2(n_2)^2} \right) \right], \left[\begin{array}{c} \left(\sqrt{\left(1 - (m_2)^2(p_1)^2\right) + \left(1 - (m_1)^2(p_2)^2\right) - (p_1)^2(p_2)^2} \right), \\ \left(\sqrt{\left(1 - (n_2)^2(r)^2\right) + \left(1 - (n_1)^2(r_2)^2\right) - (r_1)^2(r_2)^2} \right) \end{array} \right] \right\} \quad (14)$$

$$\lambda\tilde{S_1} = \left\{ \begin{array}{c} \left[\sqrt{\left(1-\left(1-(k_1)^2\right)^{\lambda}\right)}, \sqrt{\left(1-\left(1-(k_1)^2\right)^{\lambda}\right)}\right], \left[(m_1)^{\lambda}, (n_1)^{\lambda}\right], \\ \left[\sqrt{\left(1-(k_1)^2\right)^{\lambda} - \left(1-(k_1)^2-(p_1)^2\right)^{\lambda}}, \sqrt{\left(1-(l_1)^2\right)^{\lambda} - \left(1-(l_1)^2-(r_1)^2\right)^{\lambda}}\right] \end{array} \right\} \tag{15}$$

$$\tilde{S_1}^{\lambda} = \left\{ \begin{array}{c} \left[(k_1)^{\lambda}, (l_1)^{\lambda}\right], \left[\sqrt{\left(1-\left(1-(m_1)^2\right)^{\lambda}\right)}, \sqrt{\left(1-\left(1-(n_1)^2\right)^{\lambda}\right)}\right], \\ \left[\sqrt{\left(1-(m_1)^2\right)^{\lambda} - \left(1-(m_1)^2-(p_1)^2\right)^{\lambda}}, \sqrt{\left(1-(n_1)^2\right)^{\lambda} - \left(1-(n_1)^2-(r_1)^2\right)^{\lambda}}\right] \end{array} \right\} \tag{16}$$

IVSWAM operator is defined as in Eq. (17).

$$\begin{aligned} IVSWAM_w\left(\tilde{S_1}, \tilde{S_2}, \ldots \tilde{S_n}\right) &= w_1\tilde{S_1} \oplus w_2\tilde{S_2} \ldots w_n\tilde{S_n} \\ &= \left\{ \begin{array}{c} \left[\sqrt{1-\prod_{i=1}^{n}\left(1-(k_i)^2\right)^{w_i}}, \sqrt{1-\prod_{i=1}^{n}\left(1-(l_i)^2\right)^{w_i}}\right], \left[\prod_{i=1}^{n}(m_i)^{w_i}, \prod_{i=1}^{n}(n_i)^{w_i}\right], \\ \left[\sqrt{\prod_{i=1}^{n}\left(1-(k_i)^2\right)^{w_i} - \prod_{i=1}^{n}\left(1-(k_i)^2-(p_i)^2\right)^{w_i}}, \sqrt{\prod_{i=1}^{n}\left(1-(l_i)^2\right)^{w_i} - \prod_{i=1}^{n}\left(1-(l_i)^2-(r_i)^2\right)^{w_i}}\right] \end{array} \right\} \end{aligned} \tag{17}$$

Here, $w_i \epsilon [0,1]; \sum_{i=1}^{n} w_i = 1$.

Score and accuracy functions in ranking spherical fuzzy numbers are defined as in Eqs. (18, 19):

$$Score\left(\tilde{S_i}\right) = \frac{(k_i)^2 + (l_i)^2 - (m_i)^2 - (n_i)^2 - \left(\frac{p_i}{2}\right)^2 - \left(\frac{r_i}{2}\right)^2}{2} \tag{18}$$

$$Accuracy\left(\tilde{S_i}\right) = \frac{(k_i)^2 + (l_i)^2 + (m_i)^2 + (n_i)^2 + (p_i)^2 + (r_i)^2}{2} \tag{19}$$

Here, it should be noted that $\tilde{S_1} < \tilde{S_2}$ if and only if $Score\left(\tilde{S_1}\right) < Score\left(\tilde{S_2}\right)$ or $Score\left(\tilde{S_1}\right) = Score\left(\tilde{S_2}\right)$ and $Accuracy\left(\tilde{S_1}\right) < Accuracy\left(\tilde{S_2}\right)$.

2.3 IVSF-TOPSIS

In all MCDM problems, a decision matrix (in another name pay-off matrix) is required to construct the decision-making process. Since the problem that this study has dealt with is related to failure modes and effects analysis, we have designed the decision matrix whose elements include the values of all alternatives with respect to each criterion under IVSFSs. Let $F = \{f_1, f_2, \ldots, f_m\} m \geq 2$ be a set of alternatives (for this study "*failure modes*"), $RP = \{rp_1, rp_2, \ldots, rp_n\}$ be a set of criteria set (for this study "*risk parameters*"), and $w = \{w_1, w_2, \ldots, w_n\}$ be a set of criteria weights for this study "*risk parameters' weights*") that satisfy the conditions of $0 \leq w_j \leq 1$ and $\sum_{j=1}^{n} w_j = 1$.

Step 1: This step handles the construction of decision matrix. In determining the ratings of decision makers (for this study we refer to "expert") regarding alternatives with respect to the criteria, the IVSFSs-based linguistic scale given in Table 1 is used.

Let $RP_j(F_i) = \left[\mu_{ij}^{L}(u), \mu_{ij}^{U}(u)\right], \left[v_{ij}^{L}(u), v_{ij}^{U}(u)\right], \left[\pi_{ij}^{L}(u), \pi_{ij}^{U}(u)\right]$ denote the rating of a failure mode with respect to a

Table 1 The IVSFSs-based linguistic scale (Kutlu Gundogdu and Kahraman 2019a)

Linguistic term	Interval-valued spherical fuzzy number					
	$([\mu^L_{\tilde{S}_i}(u), \mu^U_{\tilde{S}_i}(u)]$		$[v^L_{\tilde{S}_i}(u), v^U_{\tilde{S}_i}(u)]$		$[\pi^L_{\tilde{S}_i}(u), \pi^U_{\tilde{S}_i}(u)]$	
Absolutely more important (AMI)	0.85	0.95	0.10	0.15	0.05	0.15
Very high important (VHI)	0.75	0.85	0.15	0.20	0.15	0.20
High important (HI)	0.65	0.75	0.20	0.25	0.20	0.25
Slightly more important (SMI)	0.55	0.65	0.25	0.30	0.25	0.30
Equally important (EI)	0.50	0.55	0.45	0.55	0.30	0.40
Slightly less important (SLI)	0.25	0.30	0.55	0.65	0.25	0.30
Low important (LI)	0.20	0.25	0.65	0.75	0.20	0.25
Very low important (VLI)	0.15	0.20	0.75	0.85	0.15	0.20
Absolutely low important (ALI)	0.10	0.15	0.85	0.95	0.05	0.15

$([\mu^L_{\tilde{S}_i}(u), \mu^U_{\tilde{S}_i}(u)]$ refer to lower and upper membership degree value of an interval-valued spherical fuzzy number, respectively. $[v^L_{\tilde{S}_i}(u), v^U_{\tilde{S}_i}(u)]$ refer to lower and upper non-membership degree value of an interval-valued spherical fuzzy number, respectively. $[\pi^L_{\tilde{S}_i}(u), \pi^U_{\tilde{S}_i}(u)]$ refer to lower and upper hesitancy degree value of an interval-valued spherical fuzzy number, respectively

risk parameter. $D = RP_j(F_i)_{mxn}$ refers to the decision matrix which is defined as follows:

$$D = RP_j(F_i)_{mxn} = \begin{bmatrix} [\mu^L_{11}(u), \mu^U_{11}(u)], [v^L_{11}(u), v^U_{11}(u)], [\pi^L_{11}(u), \pi^U_{11}(u)] & \cdots & [\mu^L_{1n}(u), \mu^U_{1n}(u)], [v^L_{1n}(u), v^U_{1n}(u)], [\pi^L_{1n}(u), \pi^U_{1n}(u)] \\ \vdots & \ddots & \vdots \\ [\mu^L_{m1}(u), \mu^U_{m1}(u)], [v^L_{m1}(u), v^U_{m1}(u)], [\pi^L_{m1}(u), \pi^U_{m1}(u)] & \cdots & [\mu^L_{mn}(u), \mu^U_{mn}(u)], [v^L_{mn}(u), v^U_{mn}(u)], [\pi^L_{mn}(u), \pi^U_{mn}(u)] \end{bmatrix} \quad (17)$$

Step 2: This step is focused on the aggregation of decision matrix which is constructed under IVSFSs. Also, the aggregation regarding evaluations of experts on risk parameter weight determination is performed in this step. We follow the aggregation procedure given in Eq. (14).

Step 3: In this step, the aggregated interval-valued spherical fuzzy decision matrix is converted into a weighted interval-valued spherical fuzzy decision matrix using Eq. (11).

Step 4: In this step, the weighted interval-valued spherical fuzzy decision matrix is defuzzified using an adaptable version of Eq. (15). It should be noted that the interval values of three membership functions are weighted interval-valued spherical fuzzy numbers which obtained in Step 3.

Step 5: This step computes the interval-valued spherical fuzzy positive ideal solution (IVSFPIS) and the interval-valued spherical fuzzy negative ideal solution (IVSFNIS) based on the score values obtained in Step 4. The formulas are given in Eqs. (18, 19) as follows:

$$F^* = \left\{ \left\{ RP_j, \langle \max_i S(RP_j(F_{iw})) \rangle | j = 1, 2, \ldots, n \right\} \right\} \quad (18)$$

$$F^- = \left\{ \left\{ RP_j, \langle \min_i S(RP_j(F_{iw})) \rangle | j = 1, 2, \ldots, n \right\} \right\} \quad (19)$$

Step 6: In this step, the distances from IVSFPIS and IVSFNIS are calculated using Eqs. (20, 21) as follows:

Table 2 Description of experts participating in the decision-making team

#	Title	Educational Stage	Age	Experience (Years)
Expert-1	Geological engineering	Master of Science	40	~ 12
Expert-2	Mining engineer	Master of Science	37	~ 10
Expert-3	Occupational safety expert & architect	PhD	48	~ 18
Expert-4	Civil engineer	Master of Science	36	~ 10

Table 3 The weight determination of experts

Score	Title	Education	Age	Experience	Total	Weight
Expert-1	3	4	3	3	13	13/51 = 0.25
Expert-2	3	4	2	3	12	13/51 = 0.24
Expert-3	3	5	3	3	14	13/51 = 0.27
Expert-4	3	4	2	3	12	13/51 = 0.24
				Total	51	

Table 4 Description of risk parameters

Risk parameter	Parameter description	Scale	References
Severity (S)	The seriousness (consequence) of the failure mode	A 10-point scale	Liu (2016), Liu et al. (2019), Yucesan and Gul (2019), Ozdemir et al. (2017), Liu et al. (2013), Bozdag et al. (2015), Park et al. (2018)
Occurrence (O)	The probability or frequency of the failure mode	A 10-point scale	Liu (2016), Liu et al. (2019), Yucesan and Gul (2019), Ozdemir et al. (2017), Liu et al. (2013), Bozdag et al. (2015), Park et al. (2018)
Detection (D)	The ability to detect the failure mode before the impact of the effect is realized	A 10-point scale	Liu (2016); Liu et al. (2019); Yucesan and Gul (2019); Ozdemir et al. (2017); Liu et al. (2013); Bozdag et al. (2015); Park et al. (2018)
Cost (C)	Percentage of the total annual budget fixed by the company for OHS measures	A 10-point scale	Di Bona et al. (2018), Von Ahsen (2008), Rezaee et al. (2017)
Prevention (P)	Ability of prevention interventions	A 10-point scale	Di Bona et al. (2018), Chen (2017)
Effectiveness (E)	Effectiveness of OHS measures (e.g., % of reduction of accidents)	A 10-point scale	Di Bona et al. (2018)

To see some details regarding the scale designed for each risk parameter, readers can refer to Table 5 and the useful references given at the last column of this table

Table 5 Scales for the applied six FMEA parameters

Rating	Risk parameter					
	Severity of effect (S)	Occurrence of failure (O)	Detection (D)	Cost (C) (%)	Prevention action opportunity (P)	Effectiveness (E)
10	Hazardous without warning	Extremely high	Absolutely impossible	91–100%	None	91–100%
9	Hazardous with warning	Very high	Very remote	81–90%	Very minor	81–90%
8	Very high	Repeated failures	Remote	71–80%	Minor	71–80%
7	High	high	Very low	61–70%	Very low	61–70%
6	Moderate	Moderately high	Low	51–60%	Low	51–60%
5	Low	Moderate	Moderate	41–50%	Moderate	41–50%
4	Very low	relatively low	Moderately high	31–40%	High	31–40%
3	Minor	Low	High	21–30%	Very high	21–30%
2	Very minor	remote	Very high	11–20%	Important high	11–20%
1	None	Nearly impossible	Almost certain	0–10%	Extremely high	0–10%

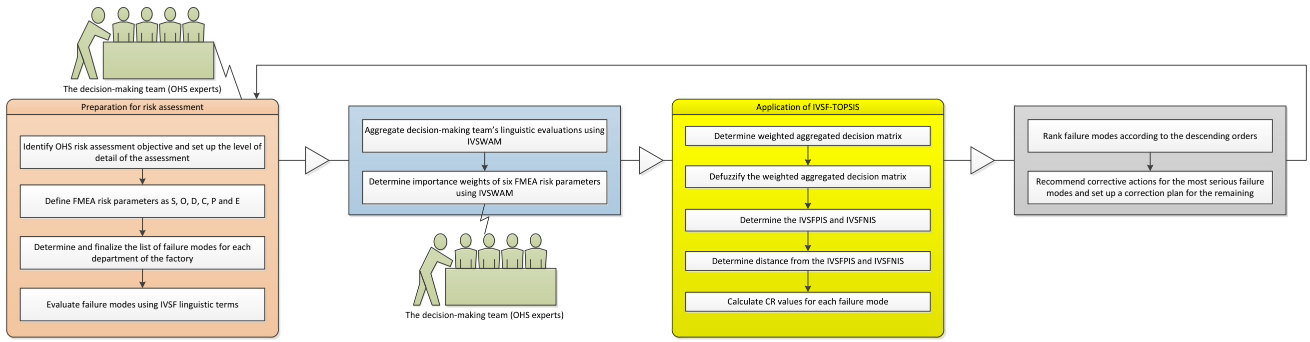

Fig. 1 Flowchart diagram of the proposed IVSF-TOPSIS-based approach

$$\begin{aligned} d\left(F_{ij}, F_j^*\right) = \frac{1}{4n}\sum_{j=1}^{n}\Bigg(\left|\left(\mu_{ij}^L\right)^2 - \left(\mu_j^*\right)^2\right| \\ + \left|\left(\mu_{ij}^U\right)^2 - \left(\mu_j^*\right)^2\right| + \left|\left(v_{ij}^L\right)^2 - \left(v_j^*\right)^2\right| \\ + \left|\left(v_{ij}^U\right)^2 - \left(v_j^*\right)^2\right| + \left|\left(\pi_{ij}^L\right)^2 - \left(\pi_j^*\right)^2\right| \\ + \left|\left(\pi_{ij}^U\right)^2 - \left(\pi_j^*\right)^2\right|\Bigg)\forall i \end{aligned} \tag{20}$$

$$\begin{aligned} d\left(F_{ij}, F_j^-\right) = \frac{1}{4n}\sum_{j=1}^{n}\Bigg(\left|\left(\mu_{ij}^L\right)^2 - \left(\mu_j^-\right)^2\right| \\ + \left|\left(\mu_{ij}^U\right)^2 - \left(\mu_j^-\right)^2\right| + \left|\left(v_{ij}^L\right)^2 - \left(v_j^-\right)^2\right| \\ + \left|\left(v_{ij}^U\right)^2 - \left(v_j^-\right)^2\right| + \left|\left(\pi_{ij}^L\right)^2 - \left(\pi_j^-\right)^2\right| \\ + \left|\left(\pi_{ij}^U\right)^2 - \left(\pi_j^-\right)^2\right|\Bigg)\forall i \end{aligned} \tag{21}$$

Step 7: This step finally calculates the closeness ratio (CR) of IVSF-TOPSIS using Eq. (22).

$$CR_i = \frac{d\left(F_{ij}, F_j^-\right)}{d\left(F_{ij}, F_j^*\right) + d\left(F_{ij}, F_j^-\right)} \tag{22}$$

Step 8: Last step prioritizes the ranking of each failure according to the descending order.

3 Demonstration of the proposed approach: failure assessment in a marble manufacturing factory

The section of "Demonstration of the proposed approach" is divided into four subsections. First, the decision-making team including well-experienced OHS experts is introduced and determination of a weight coefficient for each one is performed. Then, in the second subsection, the design of risk assessment decision-making model is addressed. In the third subsection, the application of the modified FMEA by IVSF-TOPSIS in a marble manufacturing factory is handled. Finally, a validation study between the results of this study and a benchmarking study is performed.

3.1 The decision-making team (OHS experts)

The proper selection of a decision-making team is critical for the failure assessment problem. Likewise, it will provide significant support for determining the risk parameters and failure mode list within the risk assessment decision-making model. In this case, four experts were finally chosen to participate in the decision-making process: a geological engineer, a mining engineer, an architect who is well-experienced in occupational safety and has a certificate in OHS expertise, and a civil engineer. It is noteworthy that all four experts are also consultants in occupational safety and researchers who have conducted several projects in the marble production sector. A description of the experts' profiles can be found in Table 2.

In particular, these experts were selected considering their job title, educational sage, age, and, experience (related to OHS and marble production). In the risk assessment phase of this study, it is required to use the importance weights of experts. Therefore, the priority weights of experts are calculated using the procedure of Kabir et al. (2018) and Yazdi (2018). If the years of experience are more than 30 years, a score of 5 is assigned. When the classifications are 20–29 years, 10–19 years, 6–9 years, and $\leq$ 5 years, the scores are 4, 3, 2, and 1, respectively (Kabir et al. 2018; Yazdi 2018). Similarly, if the education level is PhD, Master of Science, Bachelor, High-school, and none, the scores are 5, 4, 3, 2, and 1 assigned, respectively. Regarding age feature, if the age of expert is "more than 50," "40–49," "30–39," and "less than 30," the score of 4, 3, 2 and 1 is assigned, respectively. If the title of expert is factory manager, factory

Table 6 Failure mode list for the entire factory

Department or activity area in the factory	#	Failure mode description
Maintenance and repairing works	FM1	Non-wearing of personal protective equipment (for maintenance staff)
	FM2	Lack of maintenance instructions
	FM3	Not locking and not tagging the machine/part being serviced
	FM4	employing of unauthorized persons in maintenance work
	FM5	Maintenance, cleaning etc. at a working machine
	FM6	Failure to take necessary safety measures in welding works
	FM7	Failure to obey working rules of grinding work
	FM8	Improper use of hand tools
	FM9	Improper connection and insulation of power hand tools
	FM10	Not obeying the safety rules while working with drills
	FM11	Lack of material safety data sheet of chemicals
	FM12	Improper collection of waste oils
	FM13	Working at height
ST machine (marble block cutting machine)	FM14	Lack of emergency stop buttons on ST machines
	FM15	Lack of motor pulleys on ST machines
	FM16	To contact the saw during cutting on ST machines
	FM17	Excessive splashing and socket ejection during the cutting of ST machines
	FM18	Not to be placed iron plates under the blocks cut in ST machines
	FM19	Part splashing from the ST machine during cutting
	FM20	Intervention to the ST machine during cutting
	FM21	Electric shock
	FM22	Working environment of ST machine being watery and slippery
	FM23	Sound in the working environment of ST machine being higher than the legal limits
	FM24	Insufficient earth connection of ST machine
	FM25	Electrical installation failures of ST machine
	FM26	Falling material while loading material into ST machine
	FM27	Strike of material to the head
	FM28	Taking strips from ST machine into cross-cutting
	FM29	Intervention to large size blocks and cut strips in ST machine
	FM30	Not to be wedged at good angle of blocks cut in ST machines
	FM31	Entrance to unsafe area
Cross-cutting machine	FM32	One of the cutting machines not to have emergency stop button
	FM33	Improper control panel or incorrect use of control panel
	FM34	Lack of belt guards, pulleys, saw protection guards of cutting machines
	FM35	Intervention during cutting and running of cutting machines
	FM36	Part splashing of cutting machines during cutting
Frame saw line	FM37	Loud environment
	FM38	Falling of heavy materials
	FM39	Strike of material to the head
	FM40	Not to wear work clothes
	FM41	Lack of emergency stop button of frame saw machine
	FM42	Improper control panel or incorrect use of control panel of frame saw machine
	FM43	The lack of belt pulley safeguards of the motor of the frame saw machine
	FM44	The side of frame saw machines being lack of switches
	FM45	Contacting the blades of frame saw machine during cutting, climbing on machines
	FM46	Excessive water splashing and socket ejection of frame saw machines during cutting
	FM47	Blocks not being wedged at good angle in frame saw machines
	FM48	Breakdown of block during cutting in frame saw machines
	FM49	No insulating mat in front of bridge frame saw machine panel
	FM50	Lack of earth connection of electrical installation of frame saw machine
	FM51	Inadequate electrical installation of frame saw machine
	FM52	Working at the high by using ladder during maintenance of frame saw machine
	FM53	Working environment of frame saw machines being watery and slippery
	FM54	Lack of warning signs for hazards on and around the frame saw machine
	FM55	Moving part of frame saw machine

Table 6 (continued)

Department or activity area in the factory	#	Failure mode description
Bridge cutting machine	FM56	Loud environment
	FM57	Falling of heavy materials
	FM58	Not to wear work clothes
	FM59	Stacking strips to pallet from bridge cutting machines
	FM60	Lack of emergency stop button of bridge cutting machine
	FM61	Improper or incorrect use of bridge cutting machine control panel
	FM62	Lack of machine safeguards for bridge cutting machines
	FM63	Contact the saw during cutting of bridge cutting machine
	FM64	Excessive splashing and socket ejection of bridge cutting machines during cutting
	FM65	In bridge cutting machines, blocks not being put by wedging at good angle
	FM66	Watery and slippery working environment of the bridge cutting machine
	FM67	Lack of switches or not working switches to stop the system
	FM68	No insulating mat in front of bridge cutting machine panel
	FM69	Lack of earth connection of electrical installation of bridge cutting machines
Block area: crane	FM70	Lack of technical periodic checks of lifting vehicles such as crane etc
	FM71	Insufficient electrical installation earthling of the crane (Electric shock)
	FM72	Lack of operator documentation for crane operators
	FM73	No safety latch of crane hook
	FM74	Accidents because of not good ropes
	FM75	Not to be written lifting capacity of block stock area crane
	FM76	Lack of audible and illuminated warning systems of the crane of the block stock area
	FM77	Working under block stock crane while it is working
	FM78	No crane handling and loading, unloading instructions
	FM79	Block stock area crane's rope and grab maintenance
	FM80	Hazards during working of crane
	FM81	Occupational accidents due to lack of helmets of users and visitors
	FM82	Ensuring the use of iron-tipped boots and top boots for the employees in the block stock area
	FM83	Ladder to untrack of block stock area crane
	FM84	Not to be covered traction motors and electrical connections on the rail
	FM85	Lack of stopper wedges at the ends of the crane rail

inspector, engineer, technician or foreman, operator, respectively, the score is assigned, which takes a discrete value between 5 and 1 in the calculation. Taking into account these rules, the weights are calculated as in Table 3.

3.2 Design of risk assessment decision-making model

The pertinent scientific literature regarding FMEA served as a basis for defining the risk parameters to be included within this risk assessment decision-making model. In classical FMEA, three risk parameters of S, O, and D are used in the prioritization of failure modes (Yucesan and Gul 2019; Di Bona et al. 2018; Ozdemir et al. 2017; Liu et al. 2013, 2019; Bozdag et al. 2015; Park et al. 2018; Liu 2016). Many recent papers considered merely these three risk parameters. However, as highlighted in Introduction of this study, more and different risk parameters are required to attach to reflect the real-world problem by a clearer picture and assess the risk of failure modes precisely and in a solid way. To investigate a plenty of risk parameters in FMEA, one can refer to the study of Liu et al. (2019).

In this study, we take into consideration three more risk parameters in addition to the current three. An explanation of each FMEA risk parameter can be consulted in Table 4. The 10-point scale which each parameter has is demonstrated in Table 5. In this scale, each parameter takes values from 1 (the lowest) to 10 (the highest), while the scale of 1 indicates "None" in S, "Nearly Impossible" in O and "Almost Certain" in D, "A percentage of 1–10% which means the total annual budget fixed by the company for OHS measures" in C, "Extremely High regarding prevention action opportunity" in P, and "A percentage of 1–10% which means an extremely low effectiveness in OHS measures" in E. An eye bird view of the proposed IVSF-TOPSIS-based FMEA approach is also shown in Fig. 1.

A secondary argument in such a decision-making problem is failure modes that are assessed by the experts with respect to the six risk parameters of FMEA. After the details of six risk parameters are presented, it is time to

Table 7 Expert evaluations on risk parameters and obtained risk parameters' weights

Risk parameter	Severity	Occurrence	Detection
Expert-1	([0.75,0.85],[0.15,0.2],[0.15,0.2])	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.65,0.75],[0.2,0.25],[0.2,0.25])
Expert-2	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.55,0.65],[0.25,0.3],[0.25,0.3])
Expert-3	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.55,0.65],[0.25,0.3],[0.25,0.3])
Expert-4	([0.75,0.85],[0.15,0.2],[0.15,0.2])	([0.5,0.55],[0.45,0.55],[0.3,0.4])	([0.65,0.75],[0.2,0.25],[0.2,0.25])
Weight	([0.7,0.81],[0.17,0.22],[0.17,0.22])	([0.57,0.66],[0.27,0.33],[0.25,0.31])	([0.6,0.7],[0.22,0.27],[0.23,0.27])
Risk parameter	Cost	Prevention	Effectiveness
Expert-1	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.65,0.75],[0.2,0.25],[0.2,0.25])
Expert-2	([0.5,0.55],[0.45,0.55],[0.3,0.4])	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.55,0.65],[0.25,0.3],[0.25,0.3])
Expert-3	([0.5,0.55],[0.45,0.55],[0.3,0.4])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.25,0.3],[0.55,0.65],[0.25,0.3])
Expert-4	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.2,0.25],[0.65,0.75],[0.2,0.25])	([0.2,0.25],[0.65,0.75],[0.2,0.25])
Weight	([0.56,0.64],[0.32,0.39],[0.26,0.34])	([0.53,0.63],[0.3,0.36],[0.23,0.28])	([0.47,0.56],[0.37,0.44],[0.23,0.28])

provide a broad list of failure modes which emerged in six important processes of the factory. These processes are maintenance and repairing works, ST machine (marble block cutting machine), cross-cutting machine, frame saw line, bridge cutting machine, and block area: crane. The list of failure modes for the entire factory is given in Table 6. They are indexed from FM1 to FM85 where "FM" refers to the *failure mode*.

3.3 Application of the modified FMEA by IVSF-TOPSIS

In the first step of modified FMEA by IVSF-TOPSIS, a decision matrix in IVSFS is constructed. Four experts have rated the failure modes (a total of 85 failure modes) with respect to six risk parameters (S, O, D, C, P, and E) using the linguistic scale in Table 1. At the same time, they have rated the risk parameters using the same scale to obtain importance weights. This is indeed the second step of the approach. Also, the aggregation of four experts' evaluations is performed in this step using IVSWAM operator. Table 7 shows the evaluations of experts on risk parameters and the obtained final weights in IVSFSs.

The aggregation of decision matrix which is constructed under IVSFSs is then made. A partial demonstration for the aggregations of expert evaluations on failure modes is given in Table 8 due to space limitations.

In the third step, the aggregated decision matrix is converted into a weighted interval-valued spherical fuzzy decision matrix by taking into account the weight values obtained in Table 7. Following this step, the weighted interval-valued spherical fuzzy decision matrix is defuzzified in the fourth step. In the fifth and sixth steps, the IVSFPIS and IVSFNIS values based on the score functions and separation measures from these two values are calculated, respectively. Finally, the CR for each failure mode is obtained and the prioritization is performed. Table 9 presents the CR values and ranks for each failure mode.

The CR values of IVSF-TOPSIS indicate that the most crucial failure mode is FM5. This failure mode concerns maintaining and repairing works of the factory. It is related to the making a maintenance and cleaning activity at a working machine. The least crucial failure mode is FM11 which is identified as a lack of material safety data sheet (frequently abbreviated as MSDS) of chemicals. After determining the ranking orders of failure modes, it is also required to determine risk clusters according to the obtained CR values (Petrović et al. 2014). Considering the obtained CR values, some control measures are taken to reduce the risk into an acceptable level. For this aim, we generate five risk clusters considering CR values. The range of CR values of 85 failure modes is calculated as 0.662. Then, a class range is computed as 0.662/5 = 0.130. Thus, each interval (lower and upper bounds) for the risk clusters is obtained as in Table 10.

We investigated the histogram of CR values for the 85 failure modes, and Fig. 2 demonstrates the risk clusters and the number of failure modes that fall in the corresponding cluster. According to Fig. 2 and its related inferences, incluster-1 which consists of the most crucial failure modes includes two failure modes named FM5 and FM70. While FM5 is related to the maintenance and repairing works of the factory, FM70 concerns with the lack of technical periodic checks of lifting vehicles regarding "block area: crane" failures.

The ranking orders changing from 3 to 9 fall under the second risk cluster. These failure modes are as follows:

Table 8 Aggregations of expert evaluations on failure modes

Failure mode	Severity	Occurrence	Detection
FM1	([0.7,0.81],[0.17,0.22],[0.18,0.22])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.25,0.3],[0.55,0.65],[0.25,0.3])
FM2	([0.6,0.7],[0.22,0.27],[0.23,0.28])	([0.51,0.58],[0.39,0.48],[0.29,0.38])	([0.25,0.3],[0.55,0.65],[0.25,0.3])
FM3	([0.58,0.68],[0.24,0.29],[0.24,0.29])	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.5,0.55],[0.45,0.55],[0.3,0.4])
FM4	([0.61,0.71],[0.22,0.27],[0.22,0.27])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.25,0.3],[0.55,0.65],[0.25,0.3])
FM5	([0.85,0.95],[0.1,0.15],[0.05,0.15])	([0.85,0.95],[0.1,0.15],[0.05,0.15])	([0.11,0.16],[0.82,0.92],[0.09,0.16])
FM6	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.15,0.2],[0.75,0.85],[0.15,0.2])
FM7	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.53,0.6],[0.34,0.41],[0.28,0.35])	([0.15,0.2],[0.75,0.85],[0.15,0.2])
FM8	([0.58,0.68],[0.24,0.29],[0.24,0.29])	([0.5,0.55],[0.45,0.55],[0.3,0.4])	([0.21,0.26],[0.62,0.72],[0.21,0.26])
FM9	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.75,0.85],[0.15,0.2],[0.15,0.2])	([0.5,0.55],[0.45,0.55],[0.3,0.4])
…	…	…	…
FM77	([0.73,0.83],[0.16,0.21],[0.16,0.21])	([0.75,0.85],[0.15,0.2],[0.15,0.2])	([0.25,0.3],[0.55,0.65],[0.25,0.3])
FM78	([0.51,0.58],[0.39,0.48],[0.29,0.38])	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.15,0.2],[0.75,0.85],[0.15,0.2])
FM79	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.15,0.2],[0.75,0.85],[0.15,0.2])
FM80	([0.5,0.55],[0.45,0.55],[0.3,0.4])	([0.58,0.68],[0.24,0.29],[0.24,0.29])	([0.15,0.2],[0.75,0.85],[0.15,0.2])
FM81	([0.51,0.58],[0.39,0.48],[0.29,0.38])	([0.2,0.25],[0.65,0.75],[0.2,0.25])	([0.5,0.55],[0.45,0.55],[0.3,0.4])
FM82	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.11,0.16],[0.82,0.92],[0.09,0.16])
FM83	([0.5,0.55],[0.45,0.55],[0.3,0.4])	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.11,0.16],[0.82,0.92],[0.09,0.16])
FM84	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.11,0.16],[0.82,0.92],[0.09,0.16])
FM85	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.63,0.73],[0.21,0.26],[0.21,0.26])	([0.11,0.16],[0.82,0.92],[0.09,0.16])
	Cost	*Prevention*	*Effectiveness*
FM1	([0.51,0.58],[0.39,0.48],[0.29,0.38])	([0.81,0.92],[0.12,0.17],[0.1,0.18])	([0.65,0.75],[0.2,0.25],[0.2,0.25])
FM2	([0.25,0.3],[0.55,0.65],[0.25,0.3])	([0.63,0.73],[0.21,0.26],[0.21,0.26])	([0.6,0.7],[0.22,0.27],[0.23,0.28])
FM3	([0.15,0.2],[0.75,0.85],[0.15,0.2])	([0.85,0.95],[0.1,0.15],[0.05,0.15])	([0.65,0.75],[0.2,0.25],[0.2,0.25])
FM4	([0.53,0.6],[0.34,0.41],[0.28,0.35])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.55,0.65],[0.25,0.3],[0.25,0.3])
FM5	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.85,0.95],[0.1,0.15],[0.05,0.15])	([0.78,0.89],[0.14,0.19],[0.13,0.19])
FM6	([0.54,0.63],[0.29,0.35],[0.26,0.32])	([0.7,0.81],[0.17,0.22],[0.18,0.22])	([0.6,0.7],[0.22,0.27],[0.23,0.28])
FM7	([0.2,0.25],[0.65,0.75],[0.2,0.25])	([0.63,0.73],[0.21,0.26],[0.21,0.26])	([0.5,0.55],[0.45,0.55],[0.3,0.4])
FM8	([0.2,0.25],[0.65,0.75],[0.2,0.25])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.55,0.65],[0.25,0.3],[0.25,0.3])
FM9	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.65,0.75],[0.2,0.25],[0.2,0.25])
…	…	…	…
FM77	([0.5,0.55],[0.45,0.55],[0.3,0.4])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.65,0.75],[0.2,0.25],[0.2,0.25])
FM78	([0.33,0.38],[0.52,0.62],[0.27,0.34])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.53,0.6],[0.34,0.41],[0.28,0.35])
FM79	([0.55,0.65],[0.25,0.3],[0.25,0.3])	([0.63,0.73],[0.21,0.26],[0.21,0.26])	([0.65,0.75],[0.2,0.25],[0.2,0.25])
FM80	([0.5,0.55],[0.45,0.55],[0.3,0.4])	([0.61,0.71],[0.22,0.27],[0.22,0.27])	([0.55,0.65],[0.25,0.3],[0.25,0.3])
FM81	([0.25,0.3],[0.55,0.65],[0.25,0.3])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.5,0.55],[0.45,0.55],[0.3,0.4])
FM82	([0.23,0.28],[0.6,0.7],[0.23,0.28])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.55,0.65],[0.25,0.3],[0.25,0.3])
FM83	([0.19,0.24],[0.67,0.77],[0.19,0.24])	([0.68,0.78],[0.19,0.24],[0.19,0.24])	([0.5,0.55],[0.45,0.55],[0.3,0.4])
FM84	([0.25,0.3],[0.55,0.65],[0.25,0.3])	([0.65,0.75],[0.2,0.25],[0.2,0.25])	([0.55,0.65],[0.25,0.3],[0.25,0.3])
FM85	([0.5,0.55],[0.45,0.55],[0.3,0.4])	([0.7,0.81],[0.17,0.22],[0.18,0.22])	([0.55,0.65],[0.25,0.3],[0.25,0.3])

FM9, FM1, FM13, FM77, FM20, FM45, and FM29. The remaining failure modes in line with the clusters are readable from Table 9.

As a creative contribution to the study, an average CR value is calculated for each of the six processes of the factory. This can make it easier for decision-makers of the factory to decide which department or process will take more precautionary measures. Figure 3 shows the average CR values of each failure in each department of the observed factory. According to Fig. 3, maintenance and repairing works of the factory have the higher average CR value (0.508) followed by block area (crane operations) with an average CR value of 0.463. The bridge cutting

Table 9 CR values and rankings of failure modes

FM	CR	Rank	FM	CR	Rank	FM	CR	Rank	FM	CR	Rank	FM	CR	Rank
FM5	0.855	1	FM71	0.545	18	FM60	0.460	35	FM51	0.393	52	FM56	0.334	69
FM70	0.726	2	FM48	0.542	19	FM26	0.432	36	FM68	0.384	53	FM61	0.334	70
FM9	0.666	3	FM14	0.541	20	FM15	0.425	37	FM18	0.379	54	FM54	0.333	71
FM1	0.636	4	FM3	0.528	21	FM34	0.416	38	FM21	0.377	55	FM19	0.327	72
FM13	0.622	5	FM4	0.524	22	FM2	0.414	39	FM55	0.377	56	FM28	0.320	73
FM77	0.622	6	FM35	0.518	23	FM24	0.411	40	FM53	0.376	57	FM7	0.318	74
FM20	0.603	7	FM38	0.517	24	FM62	0.411	41	FM39	0.367	58	FM59	0.315	75
FM45	0.602	8	FM79	0.509	25	FM50	0.411	42	FM8	0.366	59	FM81	0.314	76
FM29	0.596	9	FM33	0.497	26	FM31	0.409	43	FM22	0.364	60	FM37	0.306	77
FM12	0.579	10	FM17	0.493	27	FM69	0.407	44	FM36	0.360	61	FM83	0.302	78
FM74	0.572	11	FM57	0.491	28	FM84	0.404	45	FM78	0.358	62	FM27	0.292	79
FM72	0.562	12	FM44	0.489	29	FM66	0.402	46	FM49	0.350	63	FM76	0.289	80
FM6	0.557	13	FM41	0.484	30	FM43	0.401	47	FM47	0.349	64	FM64	0.285	81
FM52	0.556	14	FM67	0.483	31	FM30	0.399	48	FM46	0.344	65	FM23	0.281	82
FM16	0.555	15	FM25	0.479	32	FM75	0.399	49	FM10	0.343	66	FM58	0.208	83
FM63	0.551	16	FM32	0.478	33	FM82	0.397	50	FM42	0.342	67	FM40	0.197	84
FM73	0.550	17	FM85	0.463	34	FM80	0.394	51	FM65	0.338	68	FM11	0.193	85

Table 10 Risk clusters and their corresponding control measures

Risk cluster	Control measure	CR interval
Cluster-1	Immediately take an action plan. Reduce the risk into an acceptable level	0.724–0.855
Cluster-2	Second cluster required to take action. Reduce the risk into an acceptable level	0.591–0.723
Cluster-3	Monitor the system and reduce the risk into an acceptable level	0.459–0.590
Cluster-4	Monitor the system changes	0.327–0.458
Cluster-5	Maintain the risk level on this level	0.193–0.326

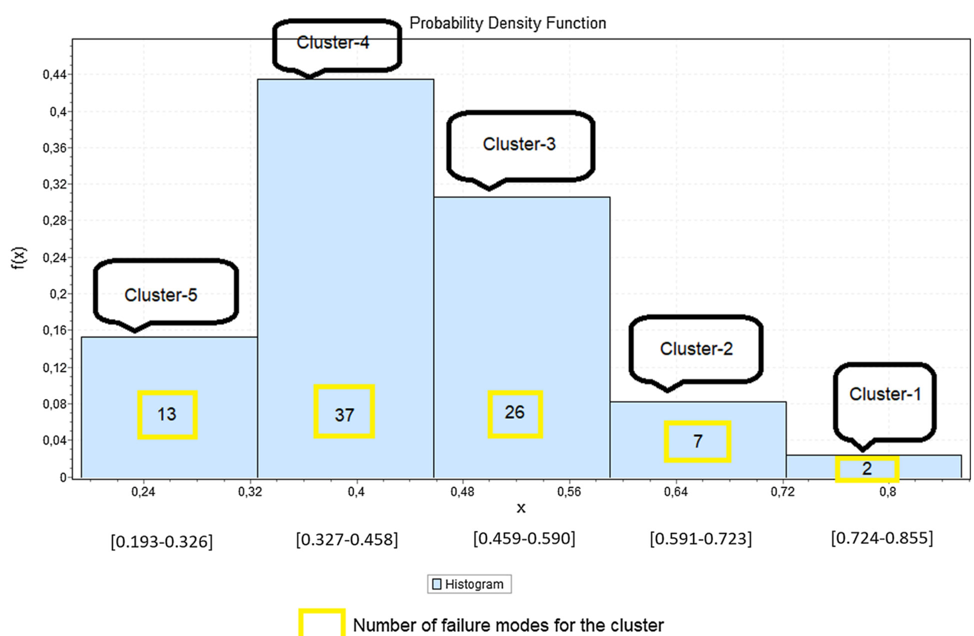

Fig. 2 Histogram of risk clusters

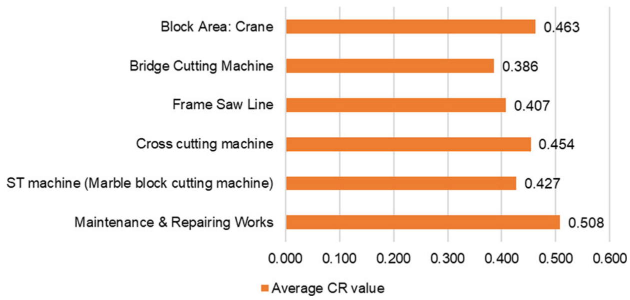

Fig. 3 Average CR value of each department/process of the factory

machine has the lowest average CR value with a value of 0.386 among the six important processes.

After carrying out the risk analysis, the most serious risks are determined by the proposed approaches. Regarding the maintenance and repair works, which had the highest possible risk rating, the following preventive measure was suggested: Personnel working in maintenance work should wear head, face, and eye protectors, gloves, and foot protectors suitable for the job. Personnel productive equipment (PPE) should be at the maximum protection level in CE standards and desired norms (Flores et al. 2016). Maintenance procedures should be established, instructions should be prepared and notified to employees, and compliance with these instructions should be constantly monitored. The part or machine being maintained should be de-energized, locked, and labeled. Employees should be informed and trained in locking, labeling, and the continuity of the necessary environment for safe maintenance work should be ensured. Authorized and trained personnel should be employed in maintenance work. Maintenance, repair, cleaning, and lubrication should not interfere with the machine in operation. Employees should always have informed about the risk. Ancillary personnel should be assigned after explaining the work to be done when necessary. Regarding the block area crane, which had the second-highest possible risk rating, the following preventive measure was suggested: Periodic checks must be carried out by the authorized mechanical engineer at least once a year by looking at the lifting tools used, the manuals of the cranes and the manufacturer. The earthing system should be checked continuously. The machine without an earthing system should not be operated. Additional ground stakes should be reinforced by driving the piles for unsuitable ground resistance points. An adequate number of crane operators with certificates must be obtained. Employees who do not have certificates must be ensured not to use these devices. The safety latches on the hooks must be continuous. Lifting should not be done without a latch. Ropes should be checked before use. The following preventive measure was suggested for the cross-cutting machine: emergency stop button must be available. The emergency stop system must be checked to ensure that it is running continuously. The protectors of the machines must be attached. Machine guards must be properly installed and work started after maintenance (Kasap et al. 2019). Machine protectors will never be removed. While the machine is running, the saw will never be contacted. Employees will be warned continuously. Warning sign must be hung. The machine should not stand in the opposite direction of the saw rotation direction. The protectors of the saws must be worn at all times. Splash-proof brushes and tires should be kept in place at all times. In order to prevent damage to the horizontal saw iron plate and the bottom must be supported (Ersoy et al. 2017). The following preventive measure was suggested for the ST machine: Protection brushes and saw protectors should be worn continuously on the machine, operators should wear protective glasses. The speed of entry of saws to stone should be controlled. Employees must be warned continuously by their supervisors not to interfere with the machine. Dispatch tables, boards, control equipment and similar installations in the workshop or in the areas accessible to workers must be placed inside the locked cabinet or cell, or their base must be covered with an insulating material that does not pass an electrical current. Warning plate must be hung for slippery ground. Employees should be provided with suitable protective headphones and delivery of them must be with a signature. Regarding the frame saw line, the following preventive measure was suggested: Noise measurement should be made in the line, headphones must be used over 85 dB, earplugs should be provided when organizational measures cannot be taken (Harger et al. 2017). Measures should be defined against the possibility of falling heavy objects, steel toe shoes and boots should be used. Lastly, emergency stop button is available on bridge cutting machines. Operation control of the buttons should be carried out at the start of each shift. All control elements on the control panel should have labels showing their duties and should be replaced if they are worn. Protectors of bridge cutting machines must be attached. Machine guards must be properly installed and work started after maintenance. Machine protectors should never be removed. While the machine is running, the saw should not be touched. Employees should be warned continuously. Warning sign must be hung. There should be no people on the side of the machine. The protectors of the saws will be worn at all times. Operators should wear safety glasses and leave a safe distance to them. The panel cover should be kept closed during operation.

3.4 Validation study on the results

In this section, some validation tests of the obtained ranking results are provided. For the first validation study,

Table 11 First validation results: comparison of rankings by two approaches

Failure mode	Rank		Failure mode	Rank		Failure mode	Rank	
	IVSF-TOPSIS	SVSF-TOPSIS		IVSF-TOPSIS	SVSF-TOPSIS		IVSF-TOPSIS	SVSF-TOPSIS
FM1	4	4	FM29	9	9	FM57	28	25
FM2	39	34	FM30	48	51	FM58	83	83
FM3	21	22	FM31	43	37	FM59	75	71
FM4	22	20	FM32	33	33	FM60	35	35
FM5	1	1	FM33	26	31	FM61	70	73
FM6	13	16	FM34	38	44	FM62	41	38
FM7	74	77	FM35	23	26	FM63	16	14
FM8	59	55	FM36	61	61	FM64	81	79
FM9	3	3	FM37	77	78	FM65	68	67
FM10	66	65	FM38	24	18	FM66	46	48
FM11	85	84	FM39	58	49	FM67	31	28
FM12	10	10	FM40	84	85	FM68	53	50
FM13	5	5	FM41	30	32	FM69	44	47
FM14	20	23	FM42	67	69	FM70	2	2
FM15	37	39	FM43	47	41	FM71	18	19
FM16	15	11	FM44	29	29	FM72	12	17
FM17	27	21	FM45	8	8	FM73	17	24
FM18	54	59	FM46	65	64	FM74	11	12
FM19	72	76	FM47	64	66	FM75	49	52
FM20	7	7	FM48	19	15	FM76	80	81
FM21	55	53	FM49	63	63	FM77	6	6
FM22	60	60	FM50	42	42	FM78	62	62
FM23	82	82	FM51	52	57	FM79	25	27
FM24	40	45	FM52	14	13	FM80	51	56
FM25	32	30	FM53	57	54	FM81	76	68
FM26	36	40	FM54	71	70	FM82	50	46
FM27	79	74	FM55	56	58	FM83	78	80
FM28	73	75	FM56	69	72	FM84	45	43
						FM85	34	36

comparative study between the results of the proposed approach (modified FMEA by IVSF-TOPSIS) and an alternative approach which uses single-valued spherical fuzzy TOPSIS (SVSF-TOPSIS). In experts' evaluations, the single-valued spherical fuzzy linguistic scale of Kutlu Gündoğdu and Kahraman (2019a, b) is used. The variations in failure mode rankings are then observed. The results are shown in Table 11.

Table 11 shows that the first 10 rankings are the same by both approaches. When we compare the results obtained by both approaches, we observe that there are very few rank variations between them. We calculated a Spearman rank correlation coefficient between the ranking results of both approaches. The coefficient is observed as 0.99132. At the same time, we also applied a correlation analysis between the CR values of both approaches. The correlation coefficient is obtained as 0.99205. Although we do not observe drastic rank variations between the current study and the benchmarking model, it can be claimed that the application of this proposed approach is new in the FMEA domain.

As a second validation study, a sensitivity analysis is made. To this end, the variation in failure mode ranking with respect to the changes in risk parameters' weights is analyzed. Regarding the sensitivity analysis, we exchange the weight vectors of the modified FMEA parameters to get combinations. As there are six risk parameters in the modified FMEA, in our case study, a total of six combinations are created. The designed weight vectors for the sensitivity analysis are given in Table 12.

Table 12 The weight vectors designed for the sensitivity analysis

Weight vector	The weight values in IVSFSs		
	S	O	D
Current vector	([0,7;0,81];[0,17;0,22];[0,17;0,22])	([0,57;0,66];[0,27;0,33];[0,25;0,31])	([0,6;0,7];[0,22;0,27];[0,23;0,27])
Weight vector-1	([0,6;0,7];[0,22;0,27];[0,23;0,27])	([0,57;0,66];[0,27;0,33];[0,25;0,31])	([0,7;0,81];[0,17;0,22];[0,17;0,22])
Weight vector-2	([0,6;0,7];[0,22;0,27];[0,23;0,27])	([0,7;0,81];[0,17;0,22];[0,17;0,22])	([0,57;0,66];[0,27;0,33];[0,25;0,31])
Weight vector-3	([0,6;0,7];[0,22;0,27];[0,23;0,27])	([0,57;0,66];[0,27;0,33];[0,25;0,31])	([0,56;0,64];[0,32;0,39];[0,26;0,34])
Weight vector-4	([0,6;0,7];[0,22;0,27];[0,23;0,27])	([0,57;0,66];[0,27;0,33];[0,25;0,31])	([0,56;0,64];[0,32;0,39];[0,26;0,34])
Weight vector-5	([0,6;0,7];[0,22;0,27];[0,23;0,27])	([0,57;0,66];[0,27;0,33];[0,25;0,31])	([0,56;0,64];[0,32;0,39];[0,26;0,34])
Weight vector	The weight values in IVSFSs C	P	E
Current vector	([0,56;0,64];[0,32;0,39];[0,26;0,34])	([0,53;0,63];[0,3;0,36];[0,23;0,28])	([0,47;0,56];[0,37;0,44];[0,23;0,28])
Weight vector-1	([0,56;0,64];[0,32;0,39];[0,26;0,34])	([0,53;0,63];[0,3;0,36];[0,23;0,28])	([0,47;0,56];[0,37;0,44];[0,23;0,28])
Weight vector-2	([0,56;0,64];[0,32;0,39];[0,26;0,34])	([0,53;0,63];[0,3;0,36];[0,23;0,28])	([0,47;0,56];[0,37;0,44];[0,23;0,28])
Weight vector-3	([0,7;0,81];[0,17;0,22];[0,17;0,22])	([0,53;0,63];[0,3;0,36];[0,23;0,28])	([0,47;0,56];[0,37;0,44];[0,23;0,28])
Weight vector-4	([0,53;0,63];[0,3;0,36];[0,23;0,28])	([0,7;0,81];[0,17;0,22];[0,17;0,22])	([0,47;0,56];[0,37;0,44];[0,23;0,28])
Weight vector-5	([0,53;0,63];[0,3;0,36];[0,23;0,28])	([0,47;0,56];[0,37;0,44];[0,23;0,28])	([0,7;0,81];[0,17;0,22];[0,17;0,22])

The ranking orders of 85 failure modes with respect to the five weight vectors are shown in Table 13. It can be observed from Table 13 that when the weight vector varies, there are variations in the ranking orders of hazards. Hence, our method is sensitive to this modified FMEA risk parameters' weights. While FM5 and FM70 are ranked as the most crucial failure modes, the least critical failure mode varies depending on the weight vector. When compared to the results with the ones similar to this study from the literature, we can say that the ranking result obtained by our proposed approach is credible and applicable. A correlation analysis is also performed between the CR value results and ranking orders with respect to weight vectors (Table 14). From this analysis, it is easily observed that both CR value and ranking results depending on six different weight vectors produce very highly correlated results.

All of the results yield correlation coefficients higher than 98%. That means a very high and positive correlation.

4 Conclusion

This paper develops a modified FMEA approach based on IVSF-TOPSIS. Proposing of this new approach, the main objectives are to cope with limitations of the traditional RPN evaluation and to help marble manufacturing stakeholders organize their safety processes systematically, analyze risks, and put into practice the precautions to reduce possible damages caused by risks.

4.1 Methodological implications

Integrating IVSFSs and TOPSIS under a modified FMEA concept, this paper proposes a novel failure assessment approach for the marble industry, which has been contributed to the safety risk assessment literature. Additionally, this paper contributes to the safety literature by the following aspects:

1. It considers three parameters called cost, prevention, and effectiveness in addition to the existed parameters of severity, occurrence, and detection in FMEA.
2. IVSWAM operator is used to calculate the relative importance of six risk parameters named as "severity, occurrence, detection, cost, prevention, and effectiveness."
3. It applies IVSF-TOPSIS to rank failure modes according to their risk level using importance values obtained by IVSWAM operator. In the previous studies, this method has not been used as a risk analysis tool and not yet applied under FMEA concept.
4. A comparative study with SVSF-TOPSIS is provided to test validity and solidity of the approach. Additionally, a comprehensive sensitivity analysis is performed to observe and analyze the variation in failure mode ranking with respect to the changes in risk parameters' weights.

Table 13 Sensitivity analysis results: Rank changes depending on the parameter's weight change

FMs	Current weight		Weight vector-1		Weight vector-2		Weight vector-3		Weight vector-4		Weight vector-5	
	CR value	Rank	CR value	Rank	CR value	Rank	CR value	Rank	CR value	Rank	CR value	Rank
FM1	0.636	4	0.621	4	0.632	4	0.624	4	0.664	3	0.631	4
FM2	0.414	39	0.402	43	0.407	44	0.394	45	0.428	42	0.422	37
FM3	0.528	21	0.539	17	0.521	23	0.514	23	0.583	10	0.537	18
FM4	0.524	22	0.516	22	0.532	21	0.523	21	0.533	19	0.517	24
FM5	0.855	1	0.831	1	0.856	1	0.828	1	0.851	1	0.846	1
FM6	0.557	13	0.546	13	0.556	16	0.543	14	0.561	13	0.543	16
FM7	0.318	74	0.309	76	0.315	74	0.299	75	0.333	76	0.312	74
FM8	0.366	59	0.355	61	0.360	62	0.349	60	0.386	58	0.364	59
FM9	0.666	3	0.675	3	0.679	3	0.659	3	0.662	4	0.670	3
FM10	0.343	66	0.355	62	0.325	72	0.349	61	0.345	70	0.343	65
FM11	0.193	85	0.187	85	0.192	85	0.201	83	0.180	85	0.186	85
FM12	0.579	10	0.570	10	0.562	13	0.592	7	0.563	12	0.567	10
FM13	0.622	5	0.614	5	0.624	6	0.619	5	0.649	5	0.623	6
FM14	0.541	20	0.544	15	0.540	19	0.531	19	0.522	23	0.543	15
FM15	0.425	37	0.416	37	0.429	38	0.391	47	0.428	41	0.408	41
FM16	0.555	15	0.538	18	0.567	12	0.542	17	0.545	17	0.536	19
FM17	0.493	27	0.468	33	0.468	35	0.457	33	0.492	30	0.494	30
FM18	0.379	54	0.362	58	0.366	58	0.352	58	0.375	61	0.368	56
FM19	0.327	72	0.344	66	0.332	70	0.325	68	0.334	75	0.337	68
FM20	0.603	7	0.587	8	0.598	8	0.591	9	0.596	9	0.602	7
FM21	0.377	55	0.375	54	0.363	60	0.379	51	0.391	55	0.386	51
FM22	0.364	60	0.358	59	0.374	56	0.335	64	0.371	64	0.351	62
FM23	0.281	82	0.277	82	0.279	81	0.258	82	0.298	80	0.272	82
FM24	0.411	40	0.407	41	0.402	48	0.401	41	0.430	40	0.390	49
FM25	0.479	32	0.475	31	0.480	32	0.484	29	0.494	29	0.476	33
FM26	0.432	36	0.427	36	0.430	37	0.427	36	0.442	36	0.422	38
FM27	0.292	79	0.287	79	0.279	82	0.274	79	0.311	79	0.291	79
FM28	0.320	73	0.317	74	0.320	73	0.317	71	0.339	73	0.308	75
FM29	0.596	9	0.586	9	0.597	9	0.590	10	0.609	7	0.597	9
FM30	0.399	48	0.398	47	0.402	46	0.399	42	0.414	47	0.394	43
FM31	0.409	43	0.408	39	0.408	42	0.418	37	0.432	37	0.428	36
FM32	0.478	33	0.475	32	0.488	31	0.473	32	0.483	33	0.489	32
FM33	0.497	26	0.494	26	0.507	26	0.493	26	0.496	28	0.507	27
FM34	0.416	38	0.415	38	0.432	36	0.416	39	0.424	44	0.412	40
FM35	0.518	23	0.503	25	0.515	25	0.500	25	0.503	25	0.517	23
FM36	0.360	61	0.357	60	0.366	59	0.356	56	0.376	60	0.361	60
FM37	0.306	77	0.302	77	0.311	76	0.293	77	0.323	78	0.306	77
FM38	0.517	24	0.513	23	0.528	22	0.519	22	0.531	21	0.535	20
FM39	0.367	58	0.362	57	0.371	57	0.353	57	0.391	56	0.367	57
FM40	0.197	84	0.205	84	0.211	84	0.199	85	0.232	84	0.207	84
FM41	0.484	30	0.481	29	0.494	30	0.479	30	0.492	31	0.494	31
FM42	0.342	67	0.340	68	0.347	66	0.329	66	0.375	62	0.339	67
FM43	0.401	47	0.400	45	0.404	45	0.410	40	0.425	43	0.405	42
FM44	0.489	29	0.485	27	0.501	27	0.489	28	0.498	26	0.505	28
FM45	0.602	8	0.589	7	0.600	7	0.592	8	0.607	8	0.601	8
FM46	0.344	65	0.341	67	0.348	65	0.326	67	0.365	66	0.341	66
FM47	0.349	64	0.346	65	0.348	64	0.341	63	0.367	65	0.346	64

Table 13 (continued)

FMs	Current weight		Weight vector-1		Weight vector-2		Weight vector-3		Weight vector-4		Weight vector-5	
	CR value	Rank	CR value	Rank	CR value	Rank	CR value	Rank	CR value	Rank	CR value	Rank
FM48	0.542	19	0.531	21	0.546	18	0.539	18	0.530	22	0.552	14
FM49	0.350	63	0.348	64	0.354	63	0.332	65	0.371	63	0.349	63
FM50	0.411	42	0.400	44	0.398	51	0.385	48	0.430	39	0.392	46
FM51	0.393	52	0.388	52	0.385	54	0.383	49	0.399	53	0.378	53
FM52	0.556	14	0.545	14	0.557	15	0.549	13	0.548	15	0.561	11
FM53	0.376	57	0.369	56	0.387	52	0.350	59	0.388	57	0.364	58
FM54	0.333	71	0.331	70	0.334	69	0.309	72	0.362	67	0.319	72
FM55	0.377	56	0.375	55	0.380	55	0.369	55	0.395	54	0.374	55
FM56	0.334	69	0.329	71	0.330	71	0.307	73	0.339	74	0.324	71
FM57	0.491	28	0.483	28	0.500	28	0.490	27	0.488	32	0.508	26
FM58	0.208	83	0.216	83	0.220	83	0.200	84	0.241	83	0.213	83
FM59	0.315	75	0.311	75	0.315	75	0.297	76	0.351	69	0.307	76
FM60	0.460	35	0.457	35	0.471	33	0.456	34	0.462	35	0.464	34
FM61	0.334	70	0.328	72	0.336	68	0.317	70	0.343	71	0.335	70
FM62	0.411	41	0.408	40	0.411	40	0.418	38	0.432	38	0.413	39
FM63	0.551	16	0.540	16	0.568	10	0.543	15	0.554	14	0.538	17
FM64	0.285	81	0.280	81	0.289	80	0.267	80	0.296	81	0.278	81
FM65	0.338	68	0.335	69	0.340	67	0.320	69	0.359	68	0.337	69
FM66	0.402	46	0.395	49	0.409	41	0.381	50	0.403	52	0.384	52
FM67	0.483	31	0.479	30	0.495	29	0.478	31	0.497	27	0.499	29
FM68	0.384	53	0.381	53	0.386	53	0.370	54	0.411	49	0.376	54
FM69	0.407	44	0.402	42	0.400	50	0.392	46	0.418	45	0.391	48
FM70	0.726	2	0.717	2	0.703	2	0.708	2	0.696	2	0.710	2
FM71	0.545	18	0.533	19	0.547	17	0.543	16	0.538	18	0.530	21
FM72	0.562	12	0.553	12	0.559	14	0.555	11	0.546	16	0.555	13
FM73	0.550	17	0.533	20	0.540	20	0.525	20	0.532	20	0.514	25
FM74	0.572	11	0.563	11	0.568	11	0.554	12	0.574	11	0.561	12
FM75	0.399	49	0.398	48	0.402	47	0.399	43	0.414	48	0.394	44
FM76	0.289	80	0.286	80	0.292	79	0.266	81	0.295	82	0.282	80
FM77	0.622	6	0.604	6	0.630	5	0.607	6	0.617	6	0.623	5
FM78	0.358	62	0.355	63	0.361	61	0.344	62	0.376	59	0.352	61
FM79	0.509	25	0.507	24	0.519	24	0.506	24	0.511	24	0.518	22
FM80	0.394	51	0.393	50	0.401	49	0.395	44	0.403	51	0.391	47
FM81	0.314	76	0.323	73	0.296	78	0.300	74	0.339	72	0.314	73
FM82	0.397	50	0.392	51	0.407	43	0.371	53	0.408	50	0.387	50
FM83	0.302	78	0.298	78	0.305	77	0.284	78	0.327	77	0.294	78
FM84	0.404	45	0.399	46	0.414	39	0.377	52	0.414	46	0.394	45
FM85	0.463	34	0.460	34	0.468	34	0.454	35	0.477	34	0.446	35

4.2 Managerial implications

The proposed approach is developed for a marble factory. Regarding control measures, this study suggests clustering of failure modes under five and determining measures with respect to this clusters. As a creative contribution to the study, an average final CR score is calculated for each of the six departments/ processes of the factory. Although it aims to mitigate the consequences of failure modes of marble production, in particular, it can be adapted to one

Table 14 Results of correlation analysis for CR value and rank

CR value	Current vector	Weight vector-1	Weight vector-2	Weight vector-3	Weight vector-4	Weight vector-5
Current vector		0.999	0.997	0.996	0.994	0.997
Weight vector-1			0.997	0.997	0.994	0.997
Weight vector-2				0.995	0.992	0.996
Weight vector-3					0.991	0.996
Weight vector-4						0.993
Weight vector-5						
Rank	**Current vector**	**Weight vector-1**	**Weight vector-2**	**Weight vector-3**	**Weight vector-4**	**Weight vector-5**
Current vector		0.997	0.993	0.993	0.993	0.994
Weight vector-1			0.992	0.995	0.994	0.996
Weight vector-2				0.988	0.988	0.991
Weight vector-3					0.990	0.995
Weight vector-4						0.991
Weight vector-5						

another industry considering characteristics of the worksite. Considering the disadvantages of classical methods such as 5 × 5 matrix, Fine-Kinney, and FMEA, this improved approach will provide field experts and other related decision makers to make more solid failure assessments to their factories.

4.3 Limitations

Current study has some limitations which the scholars and practitioners can consider in their future contributions. In our current work, we have used a procedure from the literature in weighting experts. We may suggest a novel procedure for this and make a comparison between them. Also, in determining weights of risk parameters, we have used a IVSWAM operator. We can improve and apply an independent and upgraded MCDM method such spherical AHP or best and worst method (BWM). Therefore, we are planning to uncover these limitations in our future attempts regarding development of new failure assessment approaches and applying them to fruitful areas.

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with animals performed by any of the authors.

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