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Maintenance policy selection considering resilience engineering by a new interval-valued fuzzy decision model under uncertain conditions

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Abstract. Different maintenance policies including Preventive Maintenance (PvM) and Predictive Maintenance (PdM) have been introduced to enhance the operation of systems. Maintenance professional experts have faced numerous challenges in distinguishing between proper maintenance policies among which causes of failure, accessibility, and capability of maintenance should be regarded seriously. Moreover, most organizations do not have a deliberate and compelling model for evaluating maintenance policies under uncertainty to deal with real-world conditions. The aim of this paper is to introduce a new Interval-Valued Fuzzy (IVF) decision model to select a maintenance policy based on order inclination with comparability to ideal solutions through Monte Carlo simulation. This paper introduces novel separation measures and a new IVF-distinguished index based on Possibilistic Statistical Concepts (PSCs) so that maintenance Decision-Makers (DMs) feel aided in ranking maintenance policy candidates. Also, Resilience Engineering (RE) factors are considered based on conventional evaluation criteria. Finally, the steps of the proposed IVF model-based PSCs are applied to survey a real case in the manufacturing industry. Results of the presented model are compared with those existing in the recent literature and the outcome could help maintenance personnel in identifying the best policy systematically.

1. Introduction

Appropriate maintenance not only extends the framework's lifetime, which will keep the life-cycle cost down, but also significantly contributes to the general performance of an organization in the manufacturing industry [1,2]. Moreover, proper maintenance contributes to the reduction of the total cost of production systems [3,4].

Different maintenance policies have been presented, e.g., Preventive Maintenance (PvM) and Predictive Maintenance (PdM), to enhance the reliability of a plant or a system [5]. Maintenance policy is assumed to be critical in giving direction for maintenance planning and management in how to deal with plants or systems. Optimal maintenance policy should be adopted to promote the reliability and reduce the failure risk of a plant to ensure greater

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investment. Note that every maintenance policy may enjoy some strengths and suffer weaknesses. Subsequently, selection and evaluation of a proper policy is a standout amongst the critical issues for maintenance Decision-Makers (DMs) or managers. The significance of selecting and evaluating an appropriate maintenance policy is distinctive in different manufacturing plants or systems. Evaluating and selecting a suitable maintenance policy in continuous plants or systems can be more straightforward than compound systems due to the failure of devices or equipment, thus generating a manufacturing line.

Panagiotidou and Tagaras [6] stated that an appropriate maintenance policy would lessen the likelihood of equipment failure and enhance the working condition of the equipment in a plant or system. According to Al-Najjar and Alsyouf [7], maintenance policy influences the total costs related to operating expenses; yet, the results of a wasteful maintenance policy lead directly to high maintenance costs. Numerous studies have investigated several maintenance approaches while a few have addressed the selection and evaluation of an appropriate arrangement in production systems.

The selection and evaluation of the maintenance policy does not rely on a single factor or criterion [8,9]. Consequently, maintenance approach evaluation is considered as the issue of Multi-Criteria Decision-Making (MCDM). A review of the related literature indicates that the essential factor or criterion is maintenance cost, as examined by numerous researchers; for instance, Pascual and Ortega [10] and Bartholomew-Biggs et al. [11] focused on this issue. In different studies, it was found that a few elements take fuzzy or qualitative values or forms. A few researchers including Yuniarto and Labib [12] and Marmier et al. [13] used fuzzy conditions in maintenance.

Because of the difficulty in selecting the best maintenance policy, various strategies have been proposed to overcome this deficiency [14–17]. Among the proposed strategies, the MCDM is the most popular framework that has been executed in considering the issue of selection and evaluation of maintenance candidates [18,19]. A well-known MCDM method, namely Analytical Hierarchy Process (AHP), was employed by Labib et al. [20]. Bevilacqua and Braglia [21] presented and solved the best and appropriate maintenance policy for a plant or system in the manufacturing industry. Dey [22] materialized AHP to decide on the best and suitable maintenance policies for oil pipelines. Other than utilizing AHP, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was additionally considered and utilized by Shyjith et al. [23].

Chatterjee and Kar [24] first characterized the granulation of linguistic information in heterogeneous (fuzzy, rough, interval, or crisp) contexts for group decision-making problems. Second, they constructed a flexible MCDM framework integrating the AHP with the VIekriterijumsko KOmpromisno Rangiranje (VIKOR) method in the granular domain to assess weights of different criteria and prioritize alternatives. This methodology was applied to a plastic manufacturing organization. Another study presented a hybrid algorithm based on the intuitionistic fuzzy-VIKOR method to assess five potential supplier alternatives based on five criteria and from the perspectives of four DMs in a case study [25].

An article paper in the medicinal framework suggested an algorithmic methodology with emphasis on Intuitionistic Fuzzy Soft Set (IFSS). This methodology was guided by the group decision model through the use of cardinals of IFSS. Likewise, it utilized choice matrix as a significant parameter that depended on decision parameters of individual master [26]. Another study developed a fuzzy expert system to diagnose the hypertension risk for different patients based on a set of symptoms and rules. Next, a neuro-fuzzy system was designed for the same set of symptoms and rules using three different types of learning algorithms [27]. Das et al. [28] proposed a robust decision-making approach through intuitionistic trapezoidal fuzzy number and fuzzy linguistic quantifier to compute the decision-maker's uncertain optimism degree. The applicability of the proposed approach to a site selection problem of nuclear power plant was demonstrated.

Moreover, productive endeavors directed at coordinating the MCDM strategy with other diverse systems have been made. Bertolini and Bevilacqua [29] as well as Arunraj and Maiti [30] executed the AHP by coordinating it with Goal Programming (GP) to evaluate and select suitable and appropriate maintenance alternatives. Utilizing the consolidated techniques allowed DMs to examine the issue of maintenance selection at the point of interest, considering the resource burden. Triantaphyllou et al. [31] and Luce [32] provided a selection method to choose the best effective maintenance strategy given the costs obtained by different maintenance alternatives. Murthy and Asgharizade [33] utilized game theory to direct a choice based on the client's needs to choose, having an administration contract for the maintenance of outsources.

Tahir et al. [34] utilized another maintenance optimization model to perform the calculations through a decision support system. Sachdeva et al. [35] proposed an approach that deals with the definition of a ranking of various modes of Failure Modes and Effects Analysis (FMEA) and AHP techniques. Kodali et al. [36] built up an analytic hierarchy constant sum method for supporting maintenance alternatives or systems. Meselhy et al. [37] illustrated that periodicity metrics could adequately improve their decision on selecting fitting maintenance policies.

A combination of fuzzy concepts and MCDM methods has been broadly presented for Maintenance Policy Evaluation Problem (MPEP) because of its adaptability in measuring the vagueness of the information. A combination of fuzzy logic and AHP was done in Wang and Elhag [5] and Labib [38]. A number of studies have discovered the business related to the combination of AHP and GP (e.g., [5,39]). Given that AHP is a mainstream strategy utilized as a part of taking care of MPEP, it confronts a few constraints including uneven scale judgments, instability, and imprecision in the pair-wise correlation process. Therefore, there are a few endeavors that can overcome these troubles. For instance, Pariazar et al. [40] proposed a reception of rough set theory into AHP to remove the possible irregularity existing in AHP as much as possible.

Chan and Prakash [41] employed fuzzy TOPSIS in deciding on the appropriate maintenance candidate from a monetary figure of legitimacy. Besides the mix of different methods and tools with AHP, other combined works done by Al-Najjar and Alsyouf [7], Jafari et al. [42], and Li et al. [43] exist. Pourjavad et al. [44] focused on evaluating maintenance strategy in the mining industry based on Analytical Network Process (ANP) and TOPSIS. Ding and Kamaruddin [45] developed a maintenance policy selection model with FMEA and TOPSIS. Ding et al. [46] conducted a literature review and provided directions on maintenance policy optimization over the last two decades. To choose an appropriate maintenance policy through identification of the risk of failures, Nazeri and Naderikia [47] presented a fuzzy hybrid approach consisting of FMEA, Decision-Making Trials and Evaluation Laboratory (DEMATEL) technique, and ANP. For a case study, the presented methodology was applied to the assessment and awareness of the risk of failure modes for a railroad organization.

Dealing with uncertainty in the evaluation of maintenance policies considering different assessment criteria and handling real-world conditions in manufacturing systems are the main concerns of this paper. To this end, new fuzzy modeling, called Interval-Valued Fuzzy (IVF), is proposed for complex maintenance decisions with comparability to the ideal solutions using Monte Carlo simulation. The extension of fuzzy logic is more suitable than conventional uncertainty modeling to represent the degree of certainty for each of maintenance policies in the interval form. This fuzziness may promote reliability and lessen the failure risk and low confidence in the manufacturing systems without increasing the investment. In addition, a novel possibilistic statistical decision approach based on compromise ratio modeling is presented for the selection of maintenance policy by comparability to IVF ideal solutions. Also, a new ranking index is introduced based on two high values of Possibilistic Mean (PM) and low Possibilistic Standard Deviations (PSDs). It could help support maintenance DMs in recognizing the best maintenance policy systematically. For a comprehensive assessment approach to the maintenance policy selection, this paper takes into account Resilience Engineering (RE) factors besides conventional evaluation criteria to deal with the problem.

The absence of a strategy with high capacity in analyzing and ranking maintenance policy with the highest scope of information has been disappointing in many cases. Likewise, in certain examples, quantitative and subjective criteria might be utilized continuously; this requires a technique to represent information simultaneously. Otherwise, a maintenance policy exists on the mix of proportionate quantitative and subjective criteria. A significant number of appraisal criteria for providers are quantifiable and there is no requirement for quality evaluations by DMs.

In this paper, a new decision-making model under IVF uncertainty is presented via similarity to ideal solutions with Monte Carlo simulation along with PM and PSD matrices. In addition, novel separation measures and a new IVF-distinguished index are introduced based on Possibilistic Statistical Concepts (PSCs). Characterized criteria and ambiguously characterized quantitative and subjective criteria are incorporated in the proposed decision-making process. Finally, a literature review of decision-making methods and the main contributions of this paper for selecting a maintenance policy are reported in Table 1.

The rest of this study is organized as follows. Section 2 gives an understanding of the IVF logic. Section 3 provides steps of implementing the introduced approach by clarifying alternatives and choice criteria with brief depictions. The illustrative case of MPEP in the manufacturing industry is given in Section 4. The outcomes are given and concluded in Section 5.

2. Basic definitions

Fundamental operations as well as concepts of IVFSs and possibility theory are briefly provided.

The arithmetic operations between $\tilde{A}$ and $\tilde{B}$ as two typical IVTF numbers:

$$\tilde{A} = [\tilde{A}^L, \tilde{A}^U] = [(a_1^L, a_2^L, a_3^L), (a_1^U, a_2^U, a_3^U)],$$

and:

$$\tilde{B} = [\tilde{B}^L, \tilde{B}^U] = [(b_1^L, b_2^L, b_3^L), (b_1^U, b_2^U, b_3^U)],$$

are reported as follows [55]:

Addition operation:

Table 1. Review of decision-making methods on literature for selecting maintenance policy.

Ref.	Characteristics of decision-making methods								
	Crisp data	**Fuzzy data**	**IVF numbers**	**Fuzzy possibilistic statistical approach**	**Criteria weights**	**Linguistic terms**	**Simulation analysis**	**Hybrid approach**	**Resilience engineering factors**
[21]	√	–	–	–	√	√	–	–	–
[7]	√	√	–	–	√	√	–	√	–
[48]	√	√	–	–	√	√	–	–	–
[5]	√	√	–	–	√	√	–	√	–
[34]	√	√	–	–	–	√	–	√	–
[35]	√	–	–	–	√	√	–	√	–
[36]	√	–	–	–	√	√	–	√	–
[39]	√	√	–	–	√	√	–	√	–
[30]	√	–	–	–	√	√	–	√	–
[49]	√	–	–	–	√	√	–	√	–
[44]	√	–	–	–	–	–	–	√	–
[50]	√	–	–	–	–	√	–	√	–
[41]	√	√	–	–	√	√	–	–	–
[51]	√	√	–	–	√	√	–	√	–
[46]	√	–	–	–	–	–	–	√	–
[52]	–	√	–	–	√	√	–	–	–
[47]	–	√	–	–	√	√	–	√	–
[53]	–	√	–	–	√	√	–	√	–
[54]	–	√	–	–	√	√	–	–	–
Proposed research	√	√	√	√	√	√	√	√	√

$$\tilde{A} \oplus \tilde{B} = [(a_1^L + b_1^L, a_2^L + b_2^L, a_3^L + b_3^L), (a_1^U + b_1^U, a_2^U + b_2^U, a_3^U + b_3^U)]. \quad (1)$$

Subtraction operation:

$$\tilde{A} - \tilde{B} = [(a_1^L - b_3^L, a_2^L - b_2^L, a_3^L - b_1^L), (a_1^U - b_3^U, a_2^U - b_2^U, a_3^U - b_1^U)]. \quad (2)$$

Multiplication operation:

$$\tilde{A} \otimes \tilde{B} = [(a_1^L \times b_1^L, a_2^L \times b_2^L, a_3^L \times b_3^L), (a_1^U \otimes b_1^U, a_2^U \otimes b_2^U, a_3^U \otimes b_3^U)]. \quad (3)$$

Division operation:

$$\tilde{A} \div \tilde{B} = [(a_1^L \div b_3^L, a_2^L \div b_2^L, a_3^L \div b_1^L), (a_1^U \div b_3^U, a_2^U \div b_2^U, a_3^U \div b_1^U)]. \quad (4)$$

Let $\tilde{A}$ and $\tilde{B}$ be two triangular IVF numbers; then, the distance between $\tilde{A}$ and $\tilde{B}$ is provided by Eq. (5) [56], as shown in Box I.

PM estimation and possibilistic variance of triangular fuzzy number$\tilde{A}$ are provided as follows [57–60]:

$$M(\tilde{A}) = \int_0^1 \gamma\left((a - (1-\gamma)\tau) + (a + (1-\gamma)\tau)\right) d\gamma = a + \frac{1}{6}(\sigma - \tau), \quad (6)$$

$$d(\tilde{A}, \tilde{B}) = \sqrt{\frac{1}{6}\left[(a_1^L - b_1^L)^2 + (a_2^L - b_2^L)^2 + (a_3^L - b_3^L)^2 + (a_1^U - b_1^U)^2 + (a_2^U - b_2^U)^2 + (a_3^U - b_3^U)^2\right]}. \quad (5)$$

Box I

$$Var(\tilde{A}) = \int_0^1 \gamma((a-(1-\gamma)\tau)+(a+(1-\gamma)\sigma))^2 d\gamma$$
$$= \frac{1}{24}(\sigma+\tau)^2. \quad (7)$$

3. Introduced model

In this paper, a new analysis of Monte Carlo simulation is integrated into the IVF decision to better evaluate the DM or expert preferences and opinions. In fact, unlike the previous deterministic models, the proposed modeling with the help of IVF sets can provide greater flexibility for selecting a proper maintenance policy regarding the uncertain/vague data given the lack of information. Also, possibilistic measures of mean and variance for fuzzy numbers are taken into account in the model to incorporate more complete information for possibility functions than conventional approaches. In this paper, notations of lower and upper PM values are introduced. The interval-valued PM, crisp PM value, and crisp possibilistic variance of a continuous possibility distribution are defined, which are consistent with the extension principle and well-known definitions of expectation and variance in probability theory. The theory developed in this paper is sufficiently motivated by the principles introduced in Dubois et al. [61] and by the possibilistic interpretation of the ordering introduced in Goetschel and Voxman [62].

The flowchart of the introduced model-based PM and PSD with Monte Carlo simulation is depicted in Figure 1. First, it is assumed that:

- $X = \{X_i | i = 1, \ldots, m\}$ is a set of maintenance policies;
- $C = \{C_j | j = 1, \ldots, n\}$ is a set of criteria for the MPEP.

Since the information on maintenance policy options is uncertain, DMs can take an IVF $\tilde{A}_{ij}$ to express judgment on maintenance policy option x_i through policy attribute C_j.

The MCDM of MPEP with IVF and PSCs can be given by Eq. (8) as shown in Box II, where:

$$\left[\left((a_{ij})_1^L\,(a_{ij})_2^L,(a_{ij})_3^L\right),\left((a_{ij})_1^U\,(a_{ij})_2^U,(a_{ij})_3^U\right)\right]$$
$$=\left[\left(a_{ij}^L-\tau_{ij}^L, a_{ij}^L, a_{ij}^L+\sigma_{ij}^L\right),\left(a_{ij}^U-\tau_{ij}^U, a_{ij}^U, a_{ij}^U+\sigma_{ij}^U\right)\right].$$

Steps of the introduced model for MPEP are given below:

Step 1. Identify criteria for the MPEP;

Step 2. Determine the importance of attributes j for the MPEP. Weights of criteria, w_j $(j = 1, \ldots, n)$,

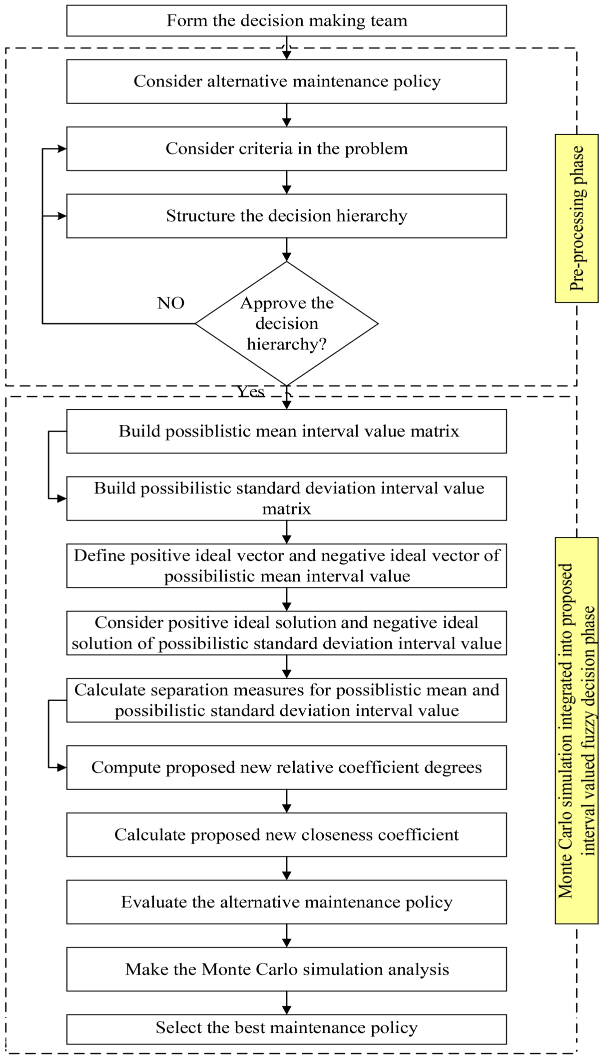


Figure 1. Flowchart of the proposed interval-valued fuzzy model with Monte Carlo simulation.

are in the range of $[0,1]$, $0 \le w_j \le 1$, $j = 1, \ldots, n$, $\sum_{i=1}^{n} w_j = 1$;

Step 3. Convert IVF matrix into a normalized matrix of maintenance policy candidates:

$$(\tilde{a}'_{ij}) = \left[\left((a'_{ij})_1^L,(a'_{ij})_2^L,(a'_{ij})_3^L\right),\left((a'_{ij})_1^U,(a'_{ij})_2^U,(a'_{ij})_3^U\right)\right]$$
$$=\left[\left(\frac{a_{ij}^L-\tau_{ij}^L}{\left(a_{ij}^U+\sigma_{ij}^U\right)^+},\frac{a_{ij}^L}{\left(a_{ij}^U+\sigma_{ij}^U\right)^+},\frac{a_{ij}^L+\sigma_{ij}^L}{\left(a_{ij}^U+\sigma_{ij}^U\right)^+}\right),\left(\frac{a_{ij}^U-\tau_{ij}^U}{\left(a_{ij}^U+\sigma_{ij}^U\right)^+},\frac{a_{ij}^U}{\left(a_{ij}^U+\sigma_{ij}^U\right)^+},\frac{a_{ij}^U+\sigma_{ij}^U}{\left(a_{ij}^U+\sigma_{ij}^U\right)^+}\right)\right],$$
$$j \in \Omega_b, \quad (9)$$

$$\tilde{A}=\left[\left((a_{ij})_1^L\,(a_{ij})_2^L\,,(a_{ij})_3^L\right),\left((a_{ij})_1^U\,(a_{ij})_2^U\,,(a_{ij})_3^U\right)\right]_{m\times n}$$

$$=\begin{bmatrix}\left[\left((a_{11})_1^L\,(a_{11})_2^L\,,(a_{11})_3^L\right),\left((a_{11})_1^U\,(a_{11})_2^U\,,(a_{11})_3^U\right)\right] & \cdots & \left[\left((a_{1n})_1^L\,(a_{1n})_2^L\,,(a_{1n})_3^L\right),\left((a_{1n})_1^U\,(a_{1n})_2^U\,,(a_{1n})_3^U\right)\right]\\ \vdots & \ddots & \vdots\\ \left[\left((a_{m1})_1^L\,(a_{m1})_2^L\,,(a_{m1})_3^L\right),\left((a_{m1})_1^U\,(a_{m1})_2^U\,,(a_{m1})_3^U\right)\right] & \cdots & \left[\left((a_{mn})_1^L\,(a_{mn})_2^L\,,(a_{mn})_3^L\right),\left((a_{mn})_1^U\,(a_{mn})_2^U\,,(a_{mn})_3^U\right)\right]\end{bmatrix} \quad (8)$$

Box II

and:

$$(\tilde{a}'_{ij})=\left[\left((a'_{ij})_1^L,(a'_{ij})_2^L,(a'_{ij})_3^L\right),\right.$$

$$\left.\left((a'_{ij})_1^U,(a'_{ij})_2^U,(a'_{ij})_3^U\right)\right]$$

$$=\left[\left(\frac{(a_{ij}^U-\tau_{ij}^U)^-}{a_{ij}^L+\sigma_{ij}^L},\frac{(a_{ij}^U-\tau_{ij}^U)^-}{a_{ij}^L},\frac{(a_{ij}^U-\tau_{ij}^U)^-}{a_{ij}^L-\tau_{ij}^L}\right)\right.$$

$$\left.\left(\frac{(a_{ij}^U-\tau_{ij}^U)^-}{a_{ij}^U+\sigma_{ij}^U},\frac{(a_{ij}^U-\tau_{ij}^U)^-}{a_{ij}^U},\frac{(a_{ij}^U-\tau_{ij}^U)^-}{a_{ij}^U-\tau_{ij}^U}\right)\right],$$

$$j\in\Omega_c, \quad (10)$$

where Ω_b and Ω_c are the sets of benefit and cost attributes for MPEP, respectively, $\left(a_{ij}^U+\sigma_{ij}^U\right)^+=\max_i\left(a_{ij}^U+\sigma_{ij}^U\right)$, $\left(a_{ij}^U-\tau_{ij}^U\right)^-=\min_i\left(a_{ij}^U-\tau_{ij}^U\right)$, $i=1,\ldots,m$. For convenience, it is shown as:

$$\left[\left((a'_{ij})_1^L\,(a'_{ij})_2^L\,,(a'_{ij})_3^L\right),\left((a'_{ij})_1^U\,(a'_{ij})_2^U\,,(a'_{ij})_3^U\right)\right]$$

$$=\left[\left(a'^L_{ij}-\tau'^L_{ij},a'^L_{ij},a'^L_{ij}+\sigma'^L_{ij}\right),\right.$$

$$\left.\left(a'^U_{ij}-\tau'^U_{ij},a'^U_{ij},a'^U_{ij}+\sigma'^U_{ij}\right)\right].$$

Step 4. Build a PM interval value matrix of MPEP. PM interval values of IVF:

$$\tilde{a}'_{ij}=\left[\left(a'^L_{ij}-\tau'^L_{ij},a'^L_{ij},a'^L_{ij}+\sigma'^L_{ij}\right),\right.$$

$$\left.\left(a'^U_{ij}-\tau'^U_{ij},a'^U_{ij},a'^U_{ij}+\sigma'^U_{ij}\right)\right],$$

are determined using Eq. (6):

$$\overline{m}_{ij}=\left[m_{ij}^L,m_{ij}^U\right]$$

$$=\left[a'^L_{ij}+\frac{1}{6}\left(\sigma'^L_{ij}-\tau'^L_{ij}\right),a'^U_{ij}+\frac{1}{6}\left(\sigma'^U_{ij}-\tau'^U_{ij}\right)\right]. \quad (11)$$

PM interval value matrix is built for MPEP as follows:

$$\overline{M}=[\bar{m}_{ij}]_{m\times n}=\begin{bmatrix}\bar{m}_{11} & \bar{m}_{12} & \ldots & \bar{m}_{1n}\\ \bar{m}_{21} & \bar{m}_{22} & \ldots & \bar{m}_{2n}\\ \vdots & \vdots & \ddots & \vdots\\ \bar{m}_{m1} & \bar{m}_{m2} & \ldots & \bar{m}_{mn}\end{bmatrix}. \quad (12)$$

Step 5. Build the SD interval value matrix of MPEP. PSD values of IVF:

$$\tilde{a}'_{ij}=\left[\left(a'^L_{ij}-\tau'^L_{ij},a'^L_{ij},a'^L_{ij}+\sigma'^L_{ij}\right),\right.$$

$$\left.\left(a'^U_{ij}-\tau'^U_{ij},a'^U_{ij},a'^U_{ij}+\sigma'^U_{ij}\right)\right],$$

are given through Eq. (7):

$$\overline{sd}_{ij}=\left[sd_{ij}^L,sd_{ij}^U\right]$$

$$=\left[\sqrt{\frac{1}{24}}\left(\sigma'^L_{ij}+\tau'^L_{ij}\right),\sqrt{\frac{1}{24}}\left(\sigma'^U_{ij}+\tau'^U_{ij}\right)\right]. \quad (13)$$

Then, the PSD interval value matrix is constructed for MPEP as follows:

$$\overline{SD}=\left[\overline{sd}_{ij}\right]_{m\times n}=\begin{bmatrix}\overline{sd}_{11} & \overline{sd}_{12} & \ldots & \overline{sd}_{1n}\\ \overline{sd}_{21} & \overline{sd}_{22} & \ldots & \overline{sd}_{2n}\\ \vdots & \vdots & \ddots & \vdots\\ \overline{sd}_{m1} & \overline{sd}_{m2} & \ldots & \overline{sd}_{mn}\end{bmatrix}. \quad (14)$$

Step 6. Consider positive-ideal and negative-ideal vectors (PIV and NIV) of PM interval values for MPEP.

$$\overline{M}^* = \left[\left(m_j^*\right)^L, \left(m_j^*\right)^U\right] = \left\{\overline{M}_1^*, \overline{M}_2^*, \ldots, \overline{M}_n^*\right\} = \left\{ \max_i \bar{m}_{ij} \middle| i = 1, 2, \ldots, m \right\}, \quad (15)$$

$$\overline{M}^- = \left[\left(m_j^-\right)^L, \left(m_j^-\right)^U\right] = \left\{\overline{M}_1^-, \overline{M}_2^-, \ldots, \overline{M}_n^-\right\} = \left\{ \min_i \bar{m}_{ij} \middle| i = 1, 2, \ldots, m \right\}. \quad (16)$$

Step 7. Define PIV and NIV of PSD interval values.

$$\overline{SD}^* = \left[\left(sd_j^*\right)^L, \left(sd_j^*\right)^U\right] = \left\{\overline{SD}_1^*, \overline{SD}_2^*, \ldots, \overline{SD}_n^*\right\} = \left\{ \min_i \overline{sd}_{ij} \middle| i = 1, 2, \ldots, m \right\}, \quad (17)$$

$$\overline{SD}^- = \left[\left(sd_j^-\right)^L, \left(sd_j^-\right)^U\right] = \left\{\overline{SD}_1^-, \overline{SD}_2^-, \ldots, \overline{SD}_n^-\right\} = \left\{ \max_i \overline{sd}_{ij} \middle| i = 1, 2, \ldots, m \right\}. \quad (18)$$

Step 8. Obtain separation measures of each maintenance policy candidate by PM and PSD interval values from PIV ($\overline{M}^*$ and $\overline{SD}^*$), respectively.

$$D_i(\bar{m}_{ij}, \overline{M}_j^*) = \sqrt{\sum_{j=1}^{n} w_j \left(\left(\left(m_j^*\right)^L - m_{ij}^L \right)^2 + w_j \left(\left(m_j^*\right)^U - m_{ij}^U \right)^2 \right)}, \quad (19)$$

$$D_i(\overline{sd}_{ij}, \overline{SD}_j^*) = \sqrt{\sum_{j=1}^{n} \left(w_j \left(\left(\left(sd_j^*\right)^L - sd_{ij}^L \right)^2 + \left(\left(sd_j^*\right)^U - sd_{ij}^U \right)^2 \right) \right)}. \quad (20)$$

Step 9. Obtain separation measures of each maintenance policy by PM and PSD interval values from NIV ($\overline{M}^-$ and $\overline{SD}_j^-$), respectively.

$$D_i(\bar{m}_{ij}, \overline{M}_j^-) = \sqrt{\sum_{j=1}^{n} w_j \left(\left(\left(m_j^-\right)^L - m_{ij}^L \right)^2 + \left(\left(m_j^-\right)^U - m_{ij}^U \right)^2 \right)}, \quad (21)$$

$$D_i(\overline{sd}_{ij}, \overline{SD}_j^-) = \sqrt{\sum_{j=1}^{n} w_j \left(\left(\left(sd_j^-\right)^L - sd_{ij}^L \right)^2 + \left(\left(sd_j^-\right)^U - sd_{ij}^U \right)^2 \right)}. \quad (22)$$

Step 10. Compute the proposed new relative coefficient degree for each maintenance policy candidate.

$$\psi_i^+ = \sqrt{\frac{D_i(\bar{m}_{ij}, \overline{M}_j^+) \times D_i(\overline{sd}_{ij}, \overline{SD}_j^+)}{D_i(\bar{m}_{ij}, \overline{M}_j^-) \times D_i(\overline{sd}_{ij}, \overline{SD}_j^-)}}, \quad (23)$$

$$\psi_i^- = \sqrt{\frac{D_i(\bar{m}_{ij}, \overline{M}_j^-) \times D_i(\overline{sd}_{ij}, \overline{SD}_j^-)}{D_i(\bar{m}_{ij}, \overline{M}_j^+) \times D_i(\overline{sd}_{ij}, \overline{SD}_j^+)}}. \quad (24)$$

Step 11. Calculate the proposed closeness coefficient CI_i for MPEP.

$$CI_i = \frac{\psi_i^-}{\psi_i^- + \psi_i^+}. \quad (25)$$

Step 12. Rank each maintenance policy candidate based on the values CI_i.

Step 13. Perform an analysis of Monte Carlo simulation and then, rank the maintenance policy candidates based on their CI_i values.

4. Case study

In this section, the MPEP is investigated in a manufacturing company in Iran from the perspective of RE. The steps of the introduced model are provided and computational results are presented in this case study for manufacturing systems with Monte Carlo simulation. Five maintenance policies are reviewed and the best policy among potential policy candidates is evaluated and selected on the basis of eleven evaluation criteria including RE factors based on safety and risk concepts. These five maintenance policies are FBM, PM, CBM, TPM, and TQMain.

The explanations of all the five maintenance policies and eleven evaluation criteria are presented in the following subsections.

4.1. Maintenance policy approaches

Maintenance policy or procedure involves arrangement of planning and decisions for the identification of faults, inquiry about causes, and execution phase of numerous inspections along with replacing devices or parts and repairing them. Five major maintenance policies are described as follows:

- Failure-Based Maintenance (FBM) (A_1) is regarded as a maintenance policy that is adopted only when a failure or breakdown occurs. In the FBM approach, just repair or substitution responses are made; however, no response is given to identify the cause of failure or to hinder it [63,64];
- Preventive Maintenance (PvM) (A_2) can be characterized as a movement that has been attempted frequently at pre-chosen intervals on a regular basis

[65,66], while the part or device properly operates to lessen the gathered deterioration, while repair is the action that involves transfering a device or part to a non-failed state upon encountering a failure [67];

- Based on Condition-Based Maintenance (CBM) policy (A_3), each of the main activities after every inspection relies on the condition of a plant or system. There is no activity or negligible activity to introduce to the framework in the same class prior to corruption. In addition, there is no essential maintenance to transfer the system to a condition equivalent to another system. This policy depends on deterministic and probabilistic models [67];
- Total Productive Maintenance (TPM) (A_4) aims to present a comprehensive methodology to accomplish a standard for executions in production versus overall effectiveness of equipment, machines, and processes [68,69]. The TPM enhances the overall effectiveness of equipment for all times by considering the dynamic contribution of operators [70];
- Total Quality Maintenance (TQMain) (A_5) can be characterized as the policy of maintenance for a plant or a system that focuses on genuine utilization of real-time data so as to detect the causes of failure through proper evaluation and to change or modify the machine state regarding the information to control and monitor damage at an early stage to suggest a quality item to a client at opportune time [63,71].

4.2. Selection criteria

The main criteria associated with the problem, i.e., MPEP, based on safety and risk concepts include the qualities, skills, and capabilities of a system with a particular focus on the RE, which can demonstrate the given task effectively. Notably, flexibility, fault tolerance, redundancy, and awareness are introduced as important factors of RE [72–75]. Brief explanations of all these main criteria based on safety and risk concepts are provided as follows (e.g., [41,46]):

- Capital cost (C_1) is a significant factor that focuses on the fixed cost;
- Running cost (C_2) is another significant factor that focuses on the variable cost to properly implement the maintenance policy;
- Awareness (C_3) is one of the important factors of RE. Gathered information gives this plausibility for the maintenance administration to ensure greater awareness of what occurs in a manufacturing system or plant;
- Redundancy (C_4) is a significant factor in RE and is considered as the ability of a manufacturing system or plant to perform quite well for an unknown period;
- Fault tolerance (C_5) is a standout factor of RE amongst the most enhanced tools and techniques for enhancing safety as well as the reliability of a manufacturing plant or system;
- Repair load (C_6) is an evaluation factor that points to the ratio of repair resources to manufacturing resources and states the traffic density regarding the repair process;
- Operator skill (C_7) is an evaluation factor that demonstrates which maintenance policy has skilled workforce;
- Flexibility (C_8) is one of the important factors of RE and is regarded as the ability of a manufacturing system or plant to make quick modifications;
- Efficiency (C_9) is an assessment factor that illustrates how a production system or plant works efficiently;
- Facility utilization (C_{10}) is an assessment factor that illustrates all the repair facilities utilized in a suitable way;
- Resource availability (C_{11}) is an evaluation factor that relates to the availability of repair workforce at the time of maintenance.

4.3. Computational results

In this case study of the decision problem, linguistic variables are reported for rating, as given in Table 2. Then, evaluation of the weights and ratings is given in Table 3. Weights of evaluation policy criteria including RE factors based on safety and risk concepts are given below:

Table 2. Linguistic variables for the values of maintenance policy candidates.

Linguistic variables	Interval-valued fuzzy numbers
Very poor	$[(0.00, 0.00, 2.00), (0.00, 0.00, 3.50)]$
Poor	$[(1.00, 2.50, 4.00), (0.00, 2.50, 6.00)]$
Fair	$[(3.50, 5.00, 6.50), (2.00, 5.00, 8.00)]$
Good	$[(6.00, 7.50, 9.00), (4.00, 7.50, 10.00)]$
Very good	$[(8.00, 10.00, 10.00), (6.50, 10.00, 10.00)]$

Table 3. Interval-valued fuzzy matrix of eleven criteria for maintenance policy evaluation problem.

Maintenance policy candidates	**Eleven criteria**			
	Capital cost	**Running cost**	**Awareness**	**Redundancy**
FBM	1.10	2.00	[(1.00,2.50,4.00), (0.00,2.50,6.00)]	[(0.00,0.00,2.00), (0.00,0.00,3.50)]
PvM	1.90	1.50	[(3.50,5.00,6.50), (2.00,5.00,8.00)]	[(6.00,7.50,9.00), (4.00,7.50,10.00)]
CBM	1.60	1.40	[(3.50,5.00,6.50), (2.00,5.00,8.00)]	[(3.50,5.00,6.50), (2.00,5.00,8.00)]
TPM	3.00	1.20	[(3.50,5.00,6.50), (2.00,5.00,8.00)]	[(6.00,7.50,9.00), (4.00,7.50,10.00)]
TQMain	3.30	1.30	[(6.00,7.50,9.00), (4.00,7.50,10.00)]	[(8.00,10.00,10.00), (6.50,10.00,10.00)]
	Fault-tolerant	**Repair load**	**Operator skill**	**Flexibility**
FBM	[(3.50,5.00,6.50), (2.00,5.00,8.00)]	[(3.50,5.00,6.50), (2.00,5.00,8.00)]	[(6.00,7.50,9.00), (4.00,7.50,10.00)]	[(0.00,0.00,2.00), (0.00,0.00,3.50)]
PvM	[(6.00,7.50,9.00), (4.00,7.50,10.00)]	[(6.00,7.50,9.00), (4.00,7.50,10.00)]	[(6.00,7.50,9.00), (4.00,7.50,10.00)]	[(0.00,0.00,2.00), (0.00,0.00,3.50)]
CBM	[(6.00,7.50,9.00), (4.00,7.50,10.00)]	[(6.00,7.50,9.00), (4.00,7.50,10.00)]	[(3.50,5.00,6.50), (2.00,5.00,8.00)]	[(6.00,7.50,9.00), (4.00,7.50,10.00)]
TPM	[(8.00,10.00,10.00), (6.50,10.00,10.00)]	[(8.00,10.00,10.00), (6.50,10.00,10.00)]	[(8.00,10.00,10.00), (6.50,10.00,10.00)]	[(3.50,5.00,6.50), (2.00,5.00,8.00)]
TQMain	[(8.00,10.00,10.00), (6.50,10.00,10.00)]	[(8.00,10.00,10.00), (6.50,10.00,10.00)]	[(6.00,7.50,9.00), (4.00,7.50,10.00)]	[(1.00,2.50,4.00), (0.00,2.50,6.00)]
	Efficiency	**Facility utilization**	**Resource availability**	
FBM	[(0.00,0.00,2.00), (0.00,0.00,3.50)]	[(0.00,0.00,2.00), (0.00,0.00,3.50)]	[(6.00,7.50,9.00), (4.00,7.50,10.00)]	
PvM	[(3.50,5.00,6.50), (2.00,5.00,8.00)]	[(0.00,0.00,2.00), (0.00,0.00,3.50)]	[(3.50,5.00,6.50), (2.00,5.00,8.00)]	
CBM	[(3.50,5.00,6.50), (2.00,5.00,8.00)]	[(1.00,2.50,4.00), (0.00,2.50,6.00)]	[(3.50,5.00,6.50), (2.00,5.00,8.00)]	
TPM	[(8.00,10.00,10.00), (6.50,10.00,10.00)]	[(6.00,7.50,9.00), (4.00,7.50,10.00)]	[(6.00,7.50,9.00), (4.00,7.50,10.00)]	
TQMain	[(8.00,10.00,10.00), (6.50,10.00,10.00)]	[(3.50,5.00,6.50), (2.00,5.00,8.00)]	[(3.50,5.00,6.50), (2.00,5.00,8.00)]	

Notes: FBM: Failure-Based Maintenance; PvM: Preventive Maintenance; CBM: Condition-Based Maintenance; TPM: Total Productive Maintenance; TQMain: Total Quality Maintenance.

$$W = \{0.112, 0.112, 0.091, 0.100, 0.091, 0.071, 0.083, 0.071, 0.078\}.$$

The IVF matrix is transformed into a normalized matrix of maintenance policy candidates, as given in Table 4. Then, IV-PM and IV-SD matrices of the MPEP are reported in Tables 5 and 6.

Then, PIV and NIV of IV-PM as well as PIV and NIV of IV-PSD are given for MPEP. Consequently, the separation measures of each maintenance policy candidate's IV-PM and IV-PSD from the PIV ($\overline{M}^*$ and $\overline{SD}^*$) and the NIV ($\overline{M}^-$ and $\overline{SD}^-$) are calculated, respectively. Finally, Table 7 shows CI_i values based on the proposed new relative coefficient degrees for maintenance policy options. Comparative analysis among the recent fuzzy decision methods through ranking of each policy for MPEP is also given in this table.

Following 5000 simulation runs, related distributions of CI_i for each maintenance policy candidate are provided to make the best decision regarding this policy evaluation and selection problem; the computational results are depicted in Figure 2. This figure illustrates the corresponding histogram for each distribution of CI_i for every maintenance policy alternative or candi-

Table 4. Normalized interval-valued fuzzy decision matrix for maintenance policy evaluation problem.

Maintenance policy candidates	Eleven criteria			
	Capital cost	**Running cost**	**Awareness**	**Redundancy**
FBM	[(1.000,1.000,1.000), (1.000,1.000,1.000)]	[(0.588,0.588,0.588), 0.588, 0.588,0.588)]	[(0.100,0.250,0.400), (0.000,0.250,0.600)]	[(0.000,0.000,0.200), (0.000,0.000,0.350)]
PvM	[(0.563,0.563,0.563), (0.563, 0.563,0.563)]	[(0.769,0.769,0.769), 0.769, 0.769,0.769)]	[(0.350,0.500,0.650), (0.200,0.500,0.800)]	[(0.600,0.750,0.900), (0.400,0.750,1.000)]
CBM	[(0.643,0.643,0.643), (0.643, 0.643,0.643)]	[(0.833,0.833,0.833), 0.833, 0.833,0.833)]	[(0.350,0.500,0.650), (0.200,0.500,0.800)]	[(0.350,0.500,0.650), (0.200,0.500,0.800)]
TPM	[(0.346,0.346,0.346), (0.346, 0.346,0.346,)]	[(1.000,1.000,1.000), 1.000, 1.000,1.000)]	[(0.350,0.500,0.650), (0.200,0.500,0.800)]	[(0.600,0.750,0.900), (0.400,0.750,1.000)]
TQMain	[(0.321,0.321,0.321), (0.321, 0.321,0.321)]	[(0.909,0.909,0.909), 0.909, 0.909,0.909)]	[(0.600,0.750,0.900), (0.400,0.750,1.000)]	[(0.800,1.000,1.000), (0.650,1.000,1.000)]
	Fault-tolerant	**Repair load**	**Operator skill**	**Flexibility**
FBM	[(0.350,0.500,0.650), (0.200,0.500,0.800)]	[(0.308,0.400,0.571), (0.250,0.400,1.000)]	[(0.600,0.750,0.900), (0.400,0.750,1.000)]	[(0.000,0.000,0.200), (0.000,0.000,0.350)]
PvM	[(0.600,0.750,0.900), (0.400,0.750,1.000)]	[(0.222,0.267,0.333), (0.200,0.267,0.500)]	[(0.600,0.750,0.900), (0.400,0.750,1.000)]	[(0.000,0.000,0.200), (0.000,0.000,0.350)]
CBM	[(0.600,0.750,0.900), (0.400,0.750,1.000)]	[(0.222,0.267,0.333), (0.200,0.267,0.500)]	[(0.350,0.500,0.650), (0.200,0.500,0.800)]	[(0.600,0.750,0.900), (0.400,0.750,1.000)]
TPM	[(0.800,1.000,1.000), (0.650,1.000,1.000)]	[(0.200,0.200,0.250), (0.200,0.200,0.308)]	[(0.800,1.000,1.000), (0.650,1.000,1.000)]	[(0.350,0.500,0.650), (0.200,0.500,0.800)]
TQMain	[(0.800,1.000,1.000), (0.650,1.000,1.000)]	[(0.200,0.200,0.250), (0.200,0.200,0.308)]	[(0.600,0.750,0.900), (0.400,0.750,1.000)]	[(0.100,0.250,0.400), (0.000,0.250,0.600)]
	Efficiency	**Facility utilization**	**Resource availability**	
FBM	[(0.000,0.000,0.200), (0.000,0.000,0.350)]	[(0.000,0.000,0.200), (0.000,0.000,0.350)]	[(0.600,0.750,0.900), (0.400,0.750,1.000)]	
PvM	[(0.350,0.500,0.650), (0.200,0.500,0.800)]	[(0.350,0.500,0.650), (0.200,0.500,0.800)]	[(0.350,0.500,0.650), (0.200,0.500,0.800)]	
CBM	[(0.350,0.500,0.650), (0.200.0.500.0.800)]	[(0.350,0.500,0.650), (0.200.0.500.0.800)]	[(0.350,0.500,0.650), (0.200,0.500,0.800)]	
TPM	[(0.800,1.000,1.000), (0.650,1.000,1.000)]	[(0.800,1.000,1.000), (0.650,1.000,1.000)]	[(0.600,0.750,0.900), (0.400,0.750,1.000)]	
TQMain	[(0.800,1.000,1.000), (0.650,1.000,1.000)]	[(0.800,1.000,1.000), (0.650,1.000,1.000)]	[(0.350,0.500,0.650), (0.200,0.500,0.800)]	

Notes: FBM: Failure-Based Maintenance, PvM: Preventive Maintenance; CBM: Condition-Based Maintenance; TPM: Total Productive Maintenance; TQMain: Total Quality Maintenance.

date. Final rankings of the maintenance policies from best to worst are as follows:

$A_4 > A_5 > A_3 > A_2 > A_1$.

4.4. Discussion of results

In this subsection, this paper conducts a sensitivity analysis to further study the impact of weights of four specific selection criteria of the RE for MPEP on final ranking. Results are given in Table 8. Assessments are done by replacing each importance of four RE factors with another importance. Some combinations of these determining factors need to be examined. It is suggested that positioning of the maintenance policy candidates be robust enough. It is worth mentioning that a robust decision-making approach through IVF sets, PSCs, and Monte Carlo simulation is employed to evaluate the uncertain process of decision-making. In addition, Table 7 and Figure 3 show the standard deviation measure considered for maintenance policy candidates to present the scattering space of positioning qualities. The standard deviation measure could push specialists to effortlessly choose the best maintenance policy among the various up-and-comers in an uncertain situation. In doing so, the proposed IVF-decision-making model with PSCs and Monte Carlo simulation has a better quality deviation with respect

Table 5. Interval valued possibilistic mean values for each maintenance policy.

Maintenance policy candidates	Eleven criteria			
	Capital cost	**Running cost**	**Awareness**	**Redundancy**
FBM	[1.000000,1.000000]	[0.588235,0.588235]	[0.588235,0.588235]	[0.033333,0.058333]
PvM	[0.562500,0.562500]	[0.769231,0.769231]	[0.769231,0.769231]	[0.750000,0.733333]
CBM	[0.642857,0.642857]	[0.833333,0.833333]	[0.833333,0.833333]	[0.500000,0.500000]
TPM	[0.346154,0.346154]	[1.000000,1.000000]	[1.000000,1.000000]	[0.750000,0.733333]
TQMain	[0.321429,0.321429]	[0.909091,0.909091]	[0.909091,0.909091]	[0.966667,0.941667]
	Fault-tolerant	**Repair load**	**Operator skill**	**Flexibility**
FBM	[0.500000,0.500000]	[0.413187,0.475000]	[0.750000,0.733333]	[0.033333,0.058333]
PvM	[0.750000,0.733333]	[0.270370,0.294444]	[0.750000,0.733333]	[0.033333,0.058333]
CBM	[0.750000,0.733333]	[0.270370,0.294444]	[0.500000,0.500000]	[0.750000,0.733333]
TPM	[0.966667,0.941667]	[0.208333,0.217949]	[0.966667,0.941667]	[0.500000,0.500000]
TQMain	[0.966667,0.941667]	[0.208333,0.217949]	[0.750000,0.733333]	[0.250000,0.266667]
	Efficiency	**Facility utilization**	**Resource availability**	–
FBM	[0.033333,0.058333]	[0.033333,0.058333]	[0.750000,0.733333]	–
PvM	[0.500000,0.500000]	[0.033333,0.058333]	[0.500000,0.500000]	–
CBM	[0.500000,0.500000]	[0.250000,0.266667]	[0.500000,0.500000]	–
TPM	[0.966667,0.941667]	[0.750000,0.733333]	[0.750000,0.733333]	–
TQMain	[0.966667,0.941667]	[0.500000,0.500000]	[0.500000,0.500000]	–

Notes: FBM: Failure-Based Maintenance; PvM: Preventive Maintenance; CBM: Condition-Based Maintenance; TPM: Total Productive Maintenance; TQMain: Total Quality Maintenance.

Table 6. Interval valued possibilistic standard deviation values for each maintenance policy.

Maintenance policy candidates	Eleven criteria			
	Capital cost	**Running cost**	**Awareness**	**Redundancy**
FBM	[0.000000,0.000000]	[0.000000,0.000000]	[0.061237,0.122474]	[0.040825,0.071443]
PvM	[0.000000,0.000000]	[0.000000,0.000000]	[0.061237,0.122474]	[0.061237,0.122474]
CBM	[0.000000,0.000000]	[0.000000,0.000000]	[0.061237,0.122474]	[0.061237,0.122474]
TPM	[0.000000,0.000000]	[0.000000,0.000000]	[0.061237, 0.122474]	[0.061237, 0.122474]
TQMain	[0.000000,0.000000]	[0.000000,0.000000]	[0.061237,0.122474]	[0.040825,0.071443]
	Fault-tolerant	**Repair load**	**Operator skill**	**Flexibility**
FBM	[0.061237,0.122474]	[0.053835,0.153093]	[0.061237,0.122474]	[0.040825,0.071443]
PvM	[0.061237,0.122474]	[0.022680,0.061237]	[0.061237,0.122474]	[0.040825,0.071443]
CBM	[0.061237,0.122474]	[0.022680,0.061237]	[0.061237,0.122474]	[0.061237,0.122474]
TPM	[0.040825,0.071443]	[0.010206,0.021983]	[0.040825,0.071443]	[0.061237,0.122474]
TQMain	[0.040825,0.071443]	[0.010206,0.021983]	[0.061237,0.122474]	[0.061237,0.122474]
	Efficiency	**Facility utilization**	**Resource availability**	–
FBM	[0.040825,0.071443]	[0.040825,0.071443]	[0.061237,0.122474]	–
PvM	[0.061237,0.122474]	[0.040825,0.071443]	[0.061237,0.122474]	–
CBM	[0.061237,0.122474]	[0.061237,0.122474]	[0.061237,0.122474]	–
TPM	[0.040825,0.071443]	[0.061237,0.122474]	[0.061237,0.122474]	–
TQMain	[0.040825,0.071443]	[0.061237,0.122474]	[0.061237,0.122474]	–

Notes: FBM: Failure-Based Maintenance; PvM: Preventive Maintenance; CBM: Condition-Based Maintenance; TPM: Total Productive Paintenance; TQMain: Total quality maintenance.

Table 7. Comparative analysis among the recent fuzzy decision methods based on the ranking of each policy for the maintenance policy evaluation problem.

Maintenance policy candidates	Ranking by proposed new interval valued fuzzy decision-making model with Monte Carlo simulation		Ranking by Chen [76] interval valued fuzzy simple additive weighting method		Ranking by Chan and Prakash [41] fuzzy distance-based method	
	Cl_i	Ranking	Score	Ranking	R_{Pi}	Ranking
FBM	0.301993	5	0.469	5	0.45	5
PvM	0.474194	4	0.544	4	0.61	4
CBM	0.532367	3	0.576	3	0.66	3
TPM	0.679232	1	0.694	1	0.75	1
TQMain	0.646888	2	0.653	2	0.73	2
The standard deviation of the scores	0.151		0.089		0.120	

Notes: FBM: Failure-Based Maintenance; PvM: Preventive Maintenance; CBM: Condition-Based Maintenance; TPM: Total Productive Maintenance; TQMain: Total Quality Maintenance.

Table 8. Analysis of the importance of four resilient engineering factors in the maintenance policy evaluation problem.

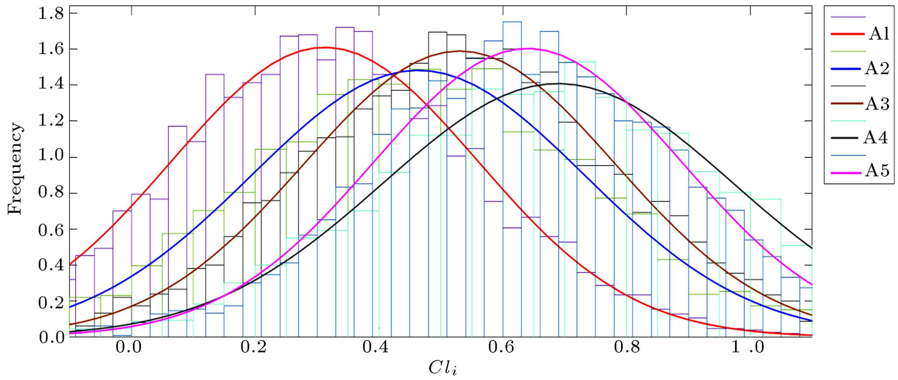
	Resilience engineering factors' weights				Maintenance policy options' values				
Conditions	Awareness	Redundancy	Fault-tolerant	Flexibility	FBM	PvM	CBM	TPM	TQMain
Main	0.091	0.100	0.100	0.071	0.302	0.474	0.532	0.679	0.647
1	0.100	0.091	0.100	0.071	0.304	0.468	0.532	0.677	0.644
2	0.100	0.100	0.091	0.071	0.302	0.474	0.532	0.678	0.647
3	0.071	0.100	0.100	0.091	0.299	0.465	0.544	0.682	0.641
4	0.091	0.100	0.100	0.071	0.302	0.474	0.532	0.679	0.647
5	0.091	0.071	0.100	0.100	0.306	0.441	0.548	0.675	0.628
6	0.091	0.100	0.071	0.100	0.297	0.459	0.547	0.678	0.638
7	0.091	0.100	0.100	0.071	0.302	0.474	0.532	0.679	0.647

Notes: FBM: Failure-Based Maintenance; PvM: Preventive Maintenance, CBM: Condition-Based Maintenance; TPM: Total Productive Maintenance, TQMain: Total Quality Maintenance.

to four different maintenance policies than two decision methods: the fuzzy distance-based method of Chan and Prakash [41] and IVF-SAW method of Chen [76].

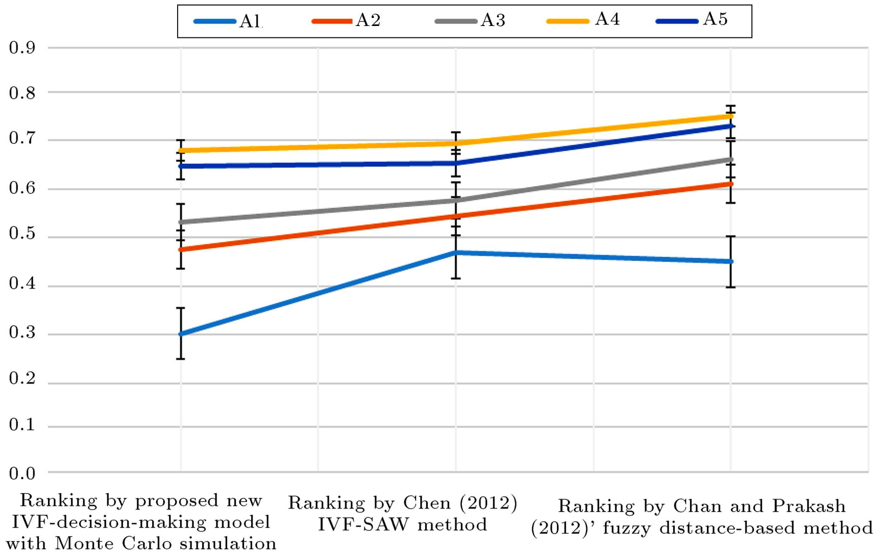
5. Conclusions

Evaluating and apprising maintenance policy among options in systems or plants is a crucial issue for maintenance managers. It is a challenging task because several conflicting criteria and maintenance policy approaches need to be considered simultaneously. This research introduced a new IVF-decision model via similarity to ideal solutions with Monte Carlo simulation for evaluating the maintenance policies. The model was presented under uncertain conditions in manufacturing systems or plants using a new analysis based on fuzzy Possibilistic Statistical Concepts (PSCs). Two IVF-PM and SD matrices were introduced. Consequently, novel separation measures were introduced for the maintenance policy selection problem regarding two high Possibilistic Mean (PM) values and low Possibilistic Standard Deviation (PSD) with IVF setting. Finally, a new IVF-distinguished index was extended based on PSCs to determine preference order of all maintenance policy candidates. This research considered Resilience Engineering (RE) factors in addition to conventional assessment criteria for this policy selection problem. Moreover, this research provided a case study in the manufacturing industry to appraise the maintenance policy options under IVF-environment. The comparative analysis among the recent fuzzy decision methods was reported. A sensitivity analysis was



FBM: Failure-Based Maintenance (A1); PvM: Preventive Maintenance (A2);
CBM: Condition-Based Maintenance (A3); TPM: Total Productive Maintenance (A4);
TQMain: Total Quality Maintenance (A5).

Figure 2. Charts of the proposed new closeness coefficient Cl_i for the maintenance policy evaluation problem.



IVF: Interval-Valued Fuzzy, SAW: Simple Additive Weighting.

Figure 3. Comparison of the scattering of the proposed method and other two decision methods on the rating of different maintenance policies.

also conducted to investigate the impacts of weights of four main RE factors on the final ranking for the maintenance policy selection problem.

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