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

N. Foroozesh[1], S.M. Mousavi[2], M. Mojtahedi[3,*], H. Gitinavard[1]

[1] *Department of Industrial Engineering and Management Systems, Amirkabir University of Technology, Tehran, Iran*
[2] *Department of Industrial Engineering, Faculty of Engineering, Shahed University, Tehran, Iran*
[3] *Faculty of Built Environment, University of New South Wales, Sydney, Australia*

Abstract
Different maintenance policies, including preventive maintenance (PvM) and predictive maintenance (PdM), are introduced to enhance the execution of systems. Maintenance professional experts have faced numerous challenges with distinguishing the proper maintenance policy, among which causes of failure, accessibility, and the 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 for the selection of maintenance policy based on order inclination with comparability to ideal solutions by Monte Carlo simulation. This paper introduces novel separation measures and a new IVF-distinguish index via possibilistic statistical concepts (PSCs) which can assist maintenance decision makers (DMs) to rank maintenance policy candidates. Also, resilience engineering (RE) factors are considered along with conventional evaluation criteria. Finally, the steps of the proposed IVF model-based PSCs are applied to survey a real case in manufacturing industry. Results of the presented model are compared with the recent literature and could help maintenance personnel in identifying the best policy systematically.

Keywords: Maintenance policy; Resilience engineering; Interval-valued fuzzy sets; Possibilistic statistical concepts; Monte Carlo simulation; Distinguish index

[*] Corresponding author. Tel.: +61 (2) 93855970.
Email addresses: sm.mousavi@shahed.ac.ir (S.M. Mousavi); m.mojtahedi@unsw.edu.au (M. Mojtahedi)

1. Introduction

Appropriate maintenance not only amplifies the framework's lifetime, which will keep the life-cycle cost down but also contributes absolutely to the general execution of the organization in the manufacturing industry [1,2]. On the other hand, maintenance additionally contributes to the total cost of production systems [3,4].

Different maintenance policies have been presented, for instance, preventive maintenance (PvM) and predictive maintenance (PdM) to enhance the reliability of a plant or a system [5]. Maintenance policy assumes a critical part in giving direction for maintenance planning and management in how to deal with plants or systems. Optimal maintenance policy should be distinguished to expand the reliability and lessen the failure risk of a plant without a large increment to be invested. Note that every maintenance policy may have strength or merits and weakness. Subsequently, selection and evaluation of the proper policy is a standout amongst the critical issues for maintenance decision makers (DMs) or managers. The level of significance of selecting and evaluating an appropriate maintenance policy is distinctive in different manufacturing plants or systems. Evaluating and selecting suitable maintenance policy within continuous plants or systems can be more straightforward than compound systems due to the failure of devices or equipment leading to a manufacturing line.

Panagiotidou and Tagaras [6] stated that an appropriate maintenance policy lessens the likelihood of equipment failure as well as enhances the working condition of the equipment in a plant or system. As indicated by Al-Najjar and Alsyouf [7], maintenance policy influences the total costs related to operating expenses, yet the results of a wasteful maintenance policy leading to the direct costs of maintenance. Numerous studies were worked with several maintenance approaches; however, several studies have covered the selection and evaluation of an appropriate arrangement in production systems.

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

Because of difficulties in selecting the best maintenance policy, various strategies have been proposed to conquer this deficiency [14-17]. Among the proposed strategies, the MCDM is the most popular frameworks that have been executed in considering selection and evaluation issue of maintenance candidates [18,19]. A well-known MCDM method, namely analytical hierarchy process (AHP), has been embraced by Labib et al. [20], and Bevilacqua and Braglia [21] presented and solved the best and appropriate maintenance policy for the plant or system in the manufacturing industry. Dey [22] actualized the AHP to decide the best and suitable maintenance for oil pipelines. Other than utilizing AHP, the technique for order of preference by similarity to ideal solution (TOPSIS) additionally has been considered and utilized by Shyjith et al. [23].

Chatterjee and Kar [24] firstly characterized the granulation of linguistic information in heterogeneous (fuzzy, rough, interval, or crisp) contexts for group decision-making problems and thereby its change in a homogenous perspective used unified granular number. Secondly, they constructed a flexible MCDM framework integrating the AHP and the VIekriterijumsko KOmpromisno Rangiranje (VIKOR) method in a granular domain to assess weights of different criteria and prioritize alternatives. This methodology was applied to a plastic manufacturing organization. A study presented a hybrid algorithm based on intuitionistic fuzzy-VIKOR method to assess five potential supplier alternatives through five criteria and four decision-makers with utilizing a case study [25].

An article in the medicinal framework suggested an algorithmic methodology dependent on intuitionistic fuzzy soft set (IFSS). This methodology was guided by the group decision model with the use of cardinals of IFSS. It likewise utilized choice matrix as a significant parameter that depended on decision parameters of individual master [26]. A study was developed a fuzzy expert system to diagnose the hypertension risk for different patients based on a set of symptoms and rules. Next, it was designed a neuro-fuzzy system 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 uncertain optimism degree of the decision maker. Applicability of the proposed approach was demonstrated on a site selection problem of nuclear power plant.

There are additionally productive endeavors that can be found in coordinating MCDM strategy with other diverse systems. Bertolini and Bevilacqua [29], and Arunraj and Maiti [30] executed the AHP by coordinating it with the goal programming (GP) to evaluate and select suitable and appropriate maintenance alternatives. Utilizing the consolidated techniques permitted the DMs to examine the maintenance selection issue in 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 where the client needs to choose, having an administration contract for outsources maintenance.

Tahir et al. [34] utilized another maintenance optimization model to do the calculations via a decision support system. Sachdeva et al. [35] proposed an approach to deal with defining a ranking of the 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] showed that periodicity metric could adequately improve their decision in selecting fitting maintenance policies.

The combination of fuzzy concepts and MCDM methods has been broadly presented for maintenance policy evaluation problem (MPEP) because of its adaptability in measuring vagueness in the information. Joining of fuzzy logic with AHP can be found in Wang et al.

[5], and Labib [38]. There are several papers discovered the business related to the combination of AHP and GP (e.g., [5,39]). Despite the fact that AHP is a mainstream strategy utilized as a part of taking care of MPEP, it confronts a few reactions including uneven scale judgments, instability, and imprecision in pair-wise correlation process. Therefore, there are a few endeavors found to defeat these troubles. For instance, Pariazar et al. [40] proposed a reception of rough set theory into AHP to take out the irregularity as often as possible existing in AHP.

Chan and Prakash [41] had displayed a utilization of fuzzy TOPSIS in deciding the appropriate maintenance candidate from a monetary figure of legitimacy. Besides the mix of different methods and tools with AHP, there were other joining works exhibited by Al-Najjar and Alsyouf [7], Jafari et al. [42] and Li et al. [43]. Pourjavad and Shirouyehzad [44] focused on evaluating maintenance strategy in the mining industry based on analytical network process (ANP) and TOPSIS. Ding et al. [45] developed a maintenance policy selection model with FMEA and TOPSIS. Ding and Kamaruddin [46] provided a literature review and directions on maintenance policy optimization in 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 consist of FMEA, decision-making trial and evaluation laboratory technique (DEMATEL), and ANP. For a case study, the presented methodology was used for assessment and assurance 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. For this purpose, a new fuzzy modeling, called interval-valued fuzzy (IVF), is proposed for the complex maintenance decisions with comparability to ideal solutions by Monte Carlo simulation. This extension of fuzzy logic is more suitable than conventional uncertainty modeling to represent this degree of certainty for each of maintenance policies by an interval form. This fuzzy can lead to expand the 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 possibilisic mean (PM) and low possibilistic standard deviations (PSDs) values. It could help support maintenance DMs in recognizing the best maintenance policy systematically. For a comprehensive assessment approach of the maintenance policy selection, this paper takes resilience engineering (RE) factors into account in addition to conventional evaluation criteria for the problem.

The absence of a strategy with high capacity in analyzing and ranking maintenance policy with the most reduced amount of information has been unsuccessful in many cases.

Likewise, in certain examples quantitative and subjective criteria might be utilized continuously; this requires a technique to represent information simultaneously. Otherwise, the maintenance policy can be found on the blend 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 matrixes. In addition, novel separation measures and a new IVF distinguish index are introduced based on possibilistic statistical concepts (PSCs). Characterized criteria and ambiguously characterized quantitative and also subjective criteria are incorporated in the proposed decision-making process. Finally, the literature review of decision-making methods and main contributions of this paper for selecting maintenance policy are reported in Table 1.

{Please insert Table 1 here.}

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

2. Basic Definitions

Fundamental operations and 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 [55],

Addition operation:

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

Subtraction operation:

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

Multiplication operation:

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

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 below [56]:

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

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

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

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

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, proposed modeling with IVF sets can provide more flexibility for the maintenance policy selection regarding the uncertain/vague data because of a lack of information than the previous deterministic models. Also, possibilistic measures of mean and variance for fuzzy numbers are taken into account in the model to incorporating 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 with 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 and Prade [61] and by the possibilistic interpretation of the ordering introduced in Goetschel and Voxman [62].

The flowchart of introduced model-based Posssiblistic mean and PSD with Monte Carlo simulation is depicted in Figure 1. Firstly, it is assumed:

$X = \{X_i | i = 1,\ldots,m\}$ as a set of maintenance policy,

$C = \{C_j \mid j = 1,\dots,n\}$ as a set of criteria for the MPEP. Since the information of maintenance policy options is uncertain, the DMs can take an IVF $\tilde{A}_{ij}$ to express judgment on maintenance policy option x_i via policy attribute C_j.

The MCDM of MPEP with IVF and PSCs can be given as:

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

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

{Please insert Figure 1 here.}

Steps of the introduced model for MPEP are given as:

Step 1. Identify criteria for the MPEP.

Step 2. Take an importance of attributes *j* for the MPEP.

Weights of criteria, $w_j (j = 1,\dots,n)$, are within $[0,1]$, $0 \le w_j \le 1$, $j = 1,\dots,n$, $\sum_{i=1}^{n} w_j = 1$.

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

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

and

$$(\tilde{a}'_{ij}) = \left[\left((a'_{ij})_1^L, (a'_{ij})_2^L, (a'_{ij})_3^L\right), \left((a'_{ij})_1^U, (a'_{ij})_2^U, (a'_{ij})_3^U\right)\right]$$
$$= \left[\left(\frac{(a_{ij}^U - \tau_{ij}^U)^-}{a_{ij}^L + \sigma_{ij}^L}, \frac{(a_{ij}^U - \tau_{ij}^U)^-}{a_{ij}^L}, \frac{(a_{ij}^U - \tau_{ij}^U)^-}{a_{ij}^L - \tau_{ij}^L}\right), \left(\frac{(a_{ij}^U - \tau_{ij}^U)^-}{a_{ij}^U + \sigma_{ij}^U}, \frac{(a_{ij}^U - \tau_{ij}^U)^-}{a_{ij}^U}, \frac{(a_{ij}^U - \tau_{ij}^U)^-}{a_{ij}^U - \tau_{ij}^U}\right)\right], \quad j \in \Omega_c \tag{10}$$

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

$$\left[\left((a'_{ij})_1^L, (a'_{ij})_2^L, (a'_{ij})_3^L\right), \left((a'_{ij})_1^U, (a'_{ij})_2^U, (a'_{ij})_3^U\right)\right] = \left[\left(a'^L_{ij} - \tau'^L_{ij}, a'^L_{ij}, a'^L_{ij} + \sigma'^L_{ij}\right), \left(a'^U_{ij} - \tau'^U_{ij}, a'^U_{ij}, a'^U_{ij} + \sigma'^U_{ij}\right)\right]$$

Step 4. Build PM interval value matrix of MPEP.

PM interval values of IVF $\tilde{a}'_{ij} = \left[\left(a'^L_{ij} - \tau'^L_{ij}, a'^L_{ij}, a'^L_{ij} + \sigma'^L_{ij}\right), \left(a'^U_{ij} - \tau'^U_{ij}, a'^U_{ij}, a'^U_{ij} + \sigma'^U_{ij}\right)\right]$ are denoted via Eq. (6):

$$\overline{m}_{ij} = \left[m_{ij}^L, m_{ij}^U\right] = \left[a'^L_{ij} + \frac{1}{6}\left(\sigma'^L_{ij} - \tau'^L_{ij}\right), a'^U_{ij} + \frac{1}{6}\left(\sigma'^U_{ij} - \tau'^U_{ij}\right)\right] \tag{11}$$

PM interval value matrix is built for MPEP as:

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

Step 5. Build SD interval value matrix of MPEP.

PSD values of IVF $\tilde{a}'_{ij} = \left[\left(a'^L_{ij} - \tau'^L_{ij}, a'^L_{ij}, a'^L_{ij} + \sigma'^L_{ij}\right), \left(a'^U_{ij} - \tau'^U_{ij}, a'^U_{ij}, a'^U_{ij} + \sigma'^U_{ij}\right)\right]$ are given via Eq. (7):

$$\overline{sd}_{ij} = \left[sd_{ij}^L, sd_{ij}^U\right] = \left[\sqrt{\frac{1}{24}}\left(\sigma'^L_{ij} + \tau'^L_{ij}\right), \sqrt{\frac{1}{24}}\left(\sigma'^U_{ij} + \tau'^U_{ij}\right)\right] \tag{13}$$

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

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

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

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

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

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 ($\bar{M}^{*}$and $\overline{SD}^{*}$) respectively.

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

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

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

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

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

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

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

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

Step 11. Calculate proposed closeness coefficient CI_i for MPEP.

$$CI_i = \frac{\psi_i^-}{\psi_i^- + \psi_i^+} \tag{25}$$

Step 12. Rank each maintenance policy candidate by the values CI_i.

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

4. Case Study

In this section, the MPEP is investigated in a manufacturing company in Iran via point of view 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 Resilience engineering factors based on safety and risk concepts. These five maintenance policies are below:

FBM, PM, CBM, TPM, and TQMain

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

4.1. Maintenance policy approaches

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

- Failure-based maintenance (FBM) (A_1) is regarded as a maintenance policy that is conducted only when a failure or breakdown happens. In FBM approach, just repair or substitution responses are made; however, no response is done to identify the reason for the failure or to hinder it [63,64].

- Preventive Maintenance (PvM) (A_2) can be characterized as a movement attempted frequently at pre-chosen intervals regularly [65,66], while the part or device is properly operating to lessen the gathered deterioration, while repair is the action to convey the device or part to a non-failed state after encountering a failure [67].
- In condition-based maintenance (CBM) policy (A_3), each main activity made after every inspection is reliant on the condition of the plant or system. There is no activity or negligible activity to introduce the framework in the same class as it was before corruption, or essential maintenance to convey the system to a condition equivalent to another system. This policy depends on deterministic and probabilistic models [67].
- Total productive maintenance (TPM) (A_4) looks to induce a comprehensive methodology towards accomplishing a standard of executions in production versus overall effectiveness of equipment, machines and processes [68,69]. The TPM enhances the overall effectiveness of equipment for all time by considering the dynamic contribution of operators [70].
- Total quality maintenance (TQMain) (A_5) can be characterized as a policy of maintenance for a plant or system that focuses on the genuine utilization of real-time data obtaining and persisting evaluation to recognize reasons of failure, 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 the opportune time [63, 71].

4.2. Selection criteria

The main criteria of the problem, i.e., MPEP, based on safety and risk concepts can be considered the qualities, skills, and capabilities of a system with a particular focus on the RE, which can demonstrate the given task effectively. Notably, that flexibility, fault-tolerant, 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 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 important factor of RE. Information gathered gives this plausibility to the maintenance administration to be aware of what occurs in a manufacturing system or plant.
- Redundancy (C_4) is a significant factor of RE that is regarded as an ability of a manufacturing system or plant, which will conduct in an attractive way for a period underdetermined working state.
- Fault-tolerant (C_5) is a standout factor of RE amongst the most enhanced tools and techniques for enhancing safety as well as the reliability of manufacturing plant or system.

- Repair load (C_6) is an evaluation factor that denotes the ratio of repair resources over the 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 workforces.
- Flexibility (C_8) is one of the important factor of RE and is regarded as the ability of a manufacturing system or plant to adopt the modifications within no time.
- 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 workforces at the time of maintenance.

4.3. Computational results

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

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

{Please insert Table 2 here.}

{Please insert Table 3 here.}

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

{Please insert Table 4 here.}

{Please insert Table 5 here.}

{Please insert Table 6 here.}

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

{Please insert Table 7 here.}

After 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 each maintenance policy alternative or candidate. Final rankings of the maintenance policies from best to the worst are as follows:

$A_4 > A_5 > A_3 > A_2 > A_1$

{Please insert Figure 2 here.}

4.4. Discussion of results

In this sub-section, this paper conducts a sensitivity analysis to further study the impact of weight for four specific selection criteria of the RE for MPEP on the final ranking. Results can be given in Table 8. Assessments are done by switching each importance of four RE factors with another importance. Some combinations of these determination factors could be examined. It relates to what we expect and it suggests that the positioning of the maintenance policy candidates has enough robustness. It is worth mentioning that a robust decision-making approach through IVF sets, PSCs and Monte Carlo simulation is employed in the proposed approach to compute the uncertain process of the decision making. In addition, Table 7 and Figure 3 show the standard deviation measure which is considered for maintenance policy candidates to present the scattering space of positioning qualities. The standard deviation measure could push the specialists to effortlessly choose the best maintenance policy among the various up-and-comers in an unsure situation. In this way, proposed IVF-decision-making model with PSCs and Monte Carlo simulation has a better-quality deviation with respect to four different maintenance policies compared with two decision methods, including Chan and Prakash [41]' fuzzy distance-based method and Chen [76]' IVF-SAW method.

{Please insert Table 8 here.}

{Please insert Figure 3 here.}

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 while considering several conflicting criteria and maintenance policy approaches. 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 by a new analysis based on fuzzy PSCs. Two IVF-PM and SD matrixes were introduced. Consequently, novel separation measures were introduced for maintenance policy selection problem regarding two high PM values and low PSD with IVF-setting. Finally, a new IVF-distinguish index was extended based on PSCs to determine preference order of all maintenance policy candidates. This research considered RE factors in addition to conventional assessment criteria for this policy selection problem. Moreover, this research provided a case study in manufacturing industry to appraise the maintenance policy options under IVF-environment. The comparative analysis among the recent fuzzy decision methods has been reported. A sensitivity analysis was also illustrated for impacts of weights of four main RE factors on the final ranking for the maintenance policy selection problem.

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Figures' captions

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

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

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

Tables' captions

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

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

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

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

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

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

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

Table 8. Analysis on the importance of four resilience engineering factors for maintenance policy evaluation problem

Figures:

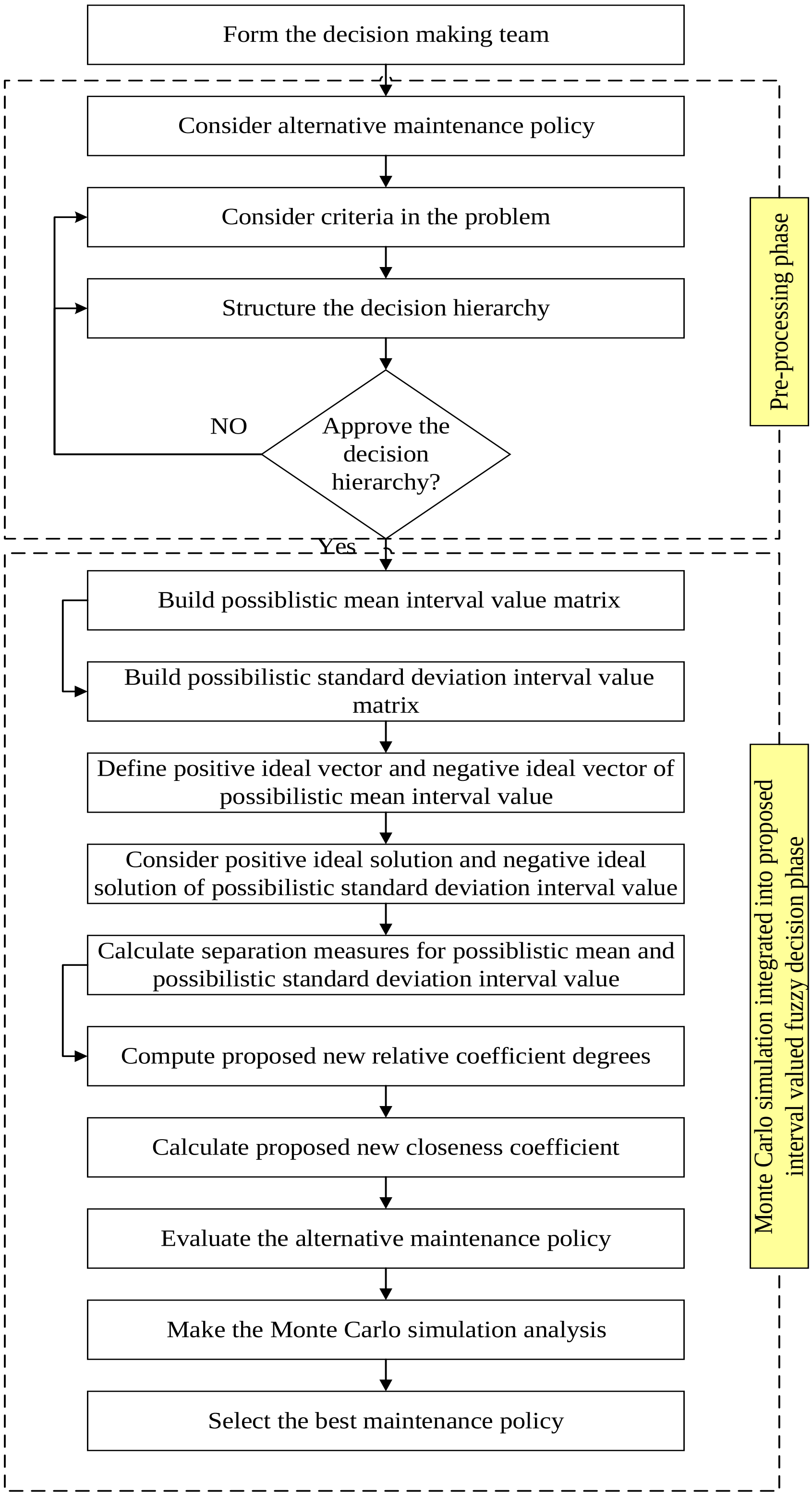
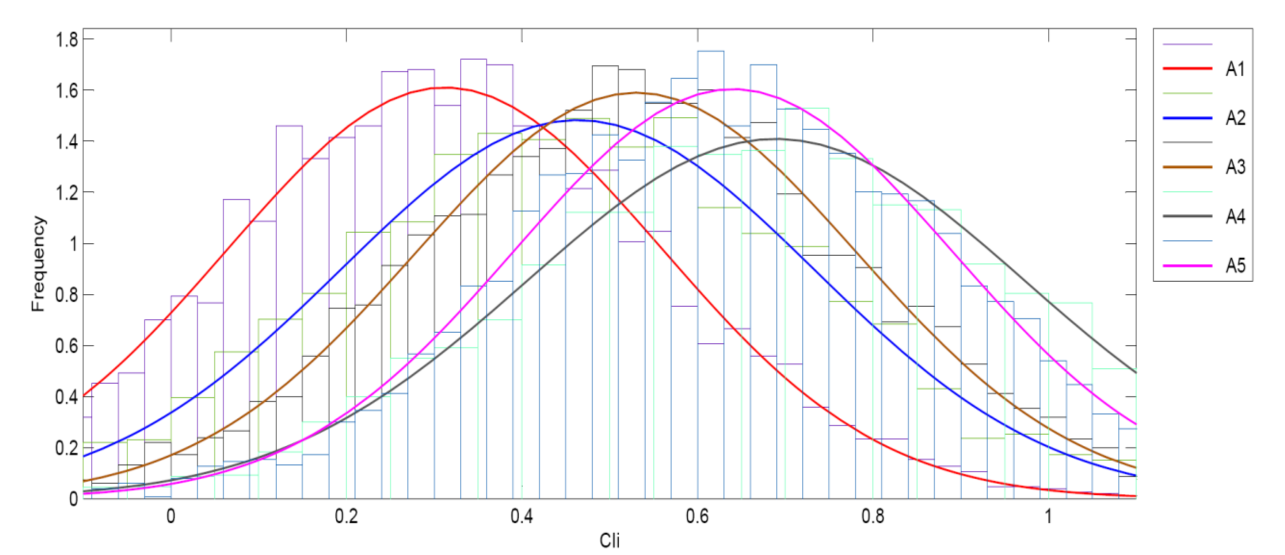
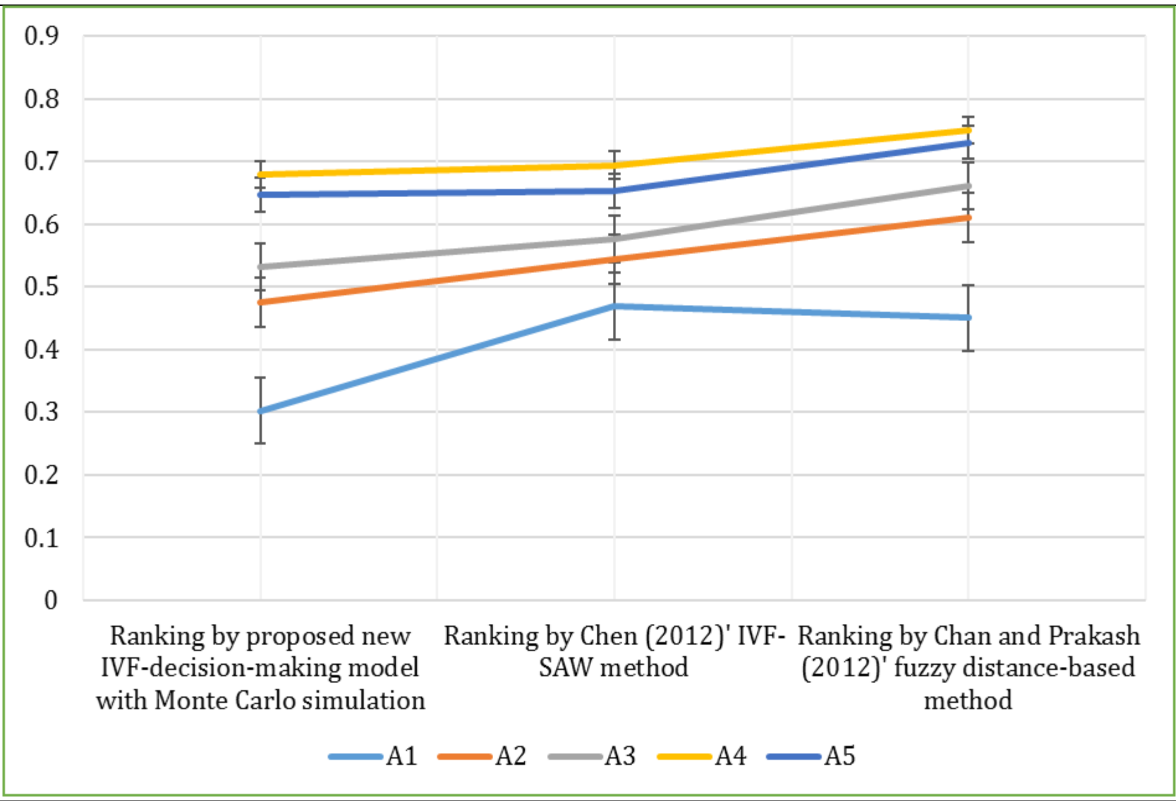

Form the decision making team
Consider alternative maintenance policy
Consider criteria in the problem
Structure the decision hierarchy
NO
Approve the decision hierarchy?
Yes
Pre-processing phase
Build possiblistic mean interval value matrix
Build possibilistic standard deviation interval value matrix
Define positive ideal vector and negative ideal vector of possibilistic mean interval value
Consider positive ideal solution and negative ideal solution of possibilistic standard deviation interval value
Calculate separation measures for possiblistic mean and possibilistic standard deviation interval value
Compute proposed new relative coefficient degrees
Calculate proposed new closeness coefficient
Evaluate the alternative maintenance policy
Make the Monte Carlo simulation analysis
Select the best maintenance policy
Monte Carlo simulation integrated into proposed interval valued fuzzy decision phase

Figure 1.



Caption
FBM: Failure-based maintenance (A_1), **PvM:** Preventive Maintenance (A_2), **CBM:** condition-based maintenance (A_3), **TPM:** Total productive maintenance (A_4), **TQMain:** Total quality maintenance (A_5).

Figure 2.



Caption
IVF: interval-valued fuzzy**, SAW**: simple additive weighting

Figure 3.

Tables:

Table 1.

Studies	Characteristics of decision-making methods								
	Crisp data	Fuzzy data	Interval-valued fuzzy 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	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 2.

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.

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.

Table 4.

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.

Table 5.

Maintenance policy candidates	Eleven selection 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.

Maintenance policy candidates	Eleven selection 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 maintenance, **TQMain:** Total quality maintenance.

Table 7.

Maintenance policy candidates	Ranking by proposed new interval valued fuzzy decision-making model with Monte Carlo simulation		Ranking by [76]' interval valued fuzzy simple additive weighting method		Ranking by Chan and Prakash [41]' fuzzy distance-based method	
	CI_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.

Conditions	Resilience engineering factors' weights				Maintenance policy options' values				
	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.

Biographies:

Nazanin Foroozesh now is a PhD student at the Department of Industrial Engineering and Management Systems, Amirkabir University of Technology, Tehran, Iran. She received her MSc from school of Industrial Engineering, University of Tehran, Iran in 2018. Her main research interests include fuzzy sets theory, multi-criteria decision-making under uncertainty, resilient and sustainable supply chain, and applied operations research. She has published several papers in reputable journals and international conference proceedings.

Seyed Meysam Mousavi is an Associate Professor at Department of Industrial Engineering, Faculty of Engineering, Shahed University in Tehran, Iran. He received a PhD degree from the School of Industrial Engineering at University of Tehran, Iran, and is currently a member of Iran's National Elite Foundation. He is the Head of Industrial Engineering Department at Shahed University and a member of the Iranian Operational Research Association. His main research interests include: cross-docking systems planning, logistics planning and scheduling, quantitative methods in project management, engineering optimization under uncertainty, and multiple criteria decisions making under uncertainty, and applied soft computing. He has published many papers and book chapters in reputable journals and international conference proceedings.

Mohammad Mojtahedi is a Senior Lecturer at the Faculty of Built Environment at the University of New South Wales, Australia. He completed his PhD in the School of Civil Engineering at The University of Sydney in 2014. He has applied his knowledge in disaster risk management and resiliency in buildings and infrastructure over the past years. He is a pioneer in Australia in combining city planning, operations research, and engineering to enhance the resilience of urban and rural buildings and infrastructure through disaster risk management. He has been invited as a keynote speaker in more than 20 international conferences and symposiums. He has received several national and international travel grants designed to provide outstanding early career researchers with the opportunities to network with reputable researchers in the field of disaster risk management and resilient built environment across the world.

Hossein Gitinavard is currently a PhD student at the Department of Industrial Engineering and Management Systems, Amirkabir University of Technology, Tehran, Iran. He received his MSc and BSc degrees from the School of Industrial Engineering, Iran University of Science and Technology, and School of Industrial Engineering, University of Tehran, Iran in 2015 and 2013, respectively. His main research interests include fuzzy sets theory, supply chain management, multi-criteria decision-making under uncertainty, and applied operations research. He has published several papers in reputable journals and international conference proceedings.