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Integration of Fuzzy PIPRECIA and Fuzzy MOORA Methods for Maintenance Strategy Selection[1]

Bakım Stratejisi Seçimi için Bulanık PIPRECIA ve Bulanık MOORA Yöntemlerinin Entegrasyonu

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Abstract

In today's competitive environment, there is a pressure on companies for reducing costs and increasing the quality by providing on time delivery. Maintenance, plays an important role in reducing cost, improving quality, reducing failures, minimizing machine downtime, increasing productivity and as a result achieving objectives of company. The aim of this paper is to select best maintenance strategy for a manufacturing company by using an integrated fuzzy MCDM (Multi-Criteria Decision Making) approach. This approach is based on fuzzy PIPRECIA (Pivot Pairwise Relative Criteria Importance Assessment) and fuzzy MOORA (Multi Objective and Optimization on the Basis of Ratio Analysis) methods. The selection of maintenance strategy is a multi-criteria decision making (MCDM) problem. As this problem includes uncertainties and difficulty in evaluating alternatives and criteria with definite expressions, fuzzy MCDM approach is proposed for selecting the best maintenance strategy. As a result of the application of the proposed integrated method in the manufacturing company, the ranking of the maintenance strategies was obtained, and predictive maintenance strategy was determined as the most appropriate maintenance strategy for the company.

Anahtar Kelimeler: *MCDM, Fuzzy sets, Fuzzy PIPRECIA Fuzzy MOORA, maintenance strategy.*

Jel Kodları: *C02, C44, M11.*

Öz

Günümüz rekabet ortamında firmalar üzerinde zamanında teslimat sağlayarak maliyetleri düşürme ve kaliteyi artırma baskısı bulunmaktadır. Bakım, maliyetlerinin düşürülmesinde, kalitenin yükseltilmesinde, arızaların azaltılmasında, makine duruş sürelerinin en aza indirilmesinde, verimliliğin artırılmasında ve bunun sonucunda işletmelerin hedeflerine ulaşmasında önemli bir rol oynamaktadır. Bu makalenin amacı, bütünleşik bulanık ÇKKV (Çok Kriterli Karar Verme) yaklaşımı kullanarak bir üretim şirketi için en iyi bakım stratejisini seçmektir. Bu yaklaşım bulanık PIPRECIA (Pivot Pairwise Relative Criteria Importance Assessment) ve bulanık MOORA (Multi Objective and Optimization on the Basis of Ratio Analysis) yöntemlerine dayanmaktadır. Bakım stratejisinin seçimi, Çok Kriterli Bir Karar Verme (ÇKKV) problemidir. Bu problem, alternatifleri ve kriterleri kesin ifadelerle değerlendirmede belirsizlikler ve zorluklar içerdiğinden, en iyi bakım stratejisini seçmek için bulanık ÇKKV yaklaşımı önerilmiştir. Önerilen entegre yöntemin üretim işletmesinde uygulanması sonucunda bakım stratejilerinin sıralaması elde edilmiş ve kestirimci bakım stratejisinin firma için en uygun bakım stratejisi olduğu belirlenmiştir.

Keywords: *ÇKKV, Bulanık kümeler, Bulanık PIPRECIA Bulanık MOORA, bakım stratejisi.*

Jel Codes: *C02, C44, M11.*

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1. INTRODUCTION

Maintenance is keeping the production system in good working order at a minimum cost. The reasons for wanting to keep machines and equipment in good operating condition are to reduce production costs, avoid late delivery, maintain high quality, and avoid production disruptions (Stevenson, 2007).

Nowadays business environment is very competitive, and businesses must reduce their costs, deliver their product on time, and increase product quality in order not to lose their competitiveness. This competition leads to a greater focus on cost reduction in processes and maintenance. The cost reduction can affect pricing immediately and this provides an advantage over competitors. Maintenance cost makes up a significant portion of the total operating cost and is therefore at the heart of most cost reduction attempts. Businesses should be careful in this regard and should not compromise on quality and safety while reducing costs. Choosing the right maintenance strategy helps the business to optimize its processes and achieve its goals. It also maintains its competitiveness by improving product quality and delivering its products on time.

Maintenance strategies can be examined in four groups: corrective maintenance, time-based preventive maintenance, condition-based maintenance, and predictive maintenance. (Wang et al., 2007). Corrective maintenance is the replacement or repair of equipment after it fails. It is an unplanned maintenance type and aimed to fix the error as soon as possible after it occurs. After the breakdown occurs, it is detected and eliminated with physical and diagnostic controls. Preventive time-based maintenance is the strategy that makes necessary parts replacements and adjustments by checking machinery and equipment at the end of predetermined periods without waiting for failure. It is periodic and scheduled depending on the availability of the maintenance personnel and to avoid interference with operating schedules. In the condition-based maintenance strategy, the actual condition of the equipment is monitored to decide what maintenance should be performed using real-time data. In this way, maintenance engineers monitor the operation of critical systems in real-time and identify potential failures in components and it allows for more convenient planning of service or repair intervals. Predictive maintenance strategy allows you to predict possible breakdowns, make production plans accordingly, and order spare parts in advance. It is based on historical data and analysis for predicting when equipment is about to fail. Better failure predictions make the maintenance strategy more effective.

In the process of maintenance strategy selection, multiple criteria must be considered. Therefore, the maintenance strategy selection problem can be solved by Multi-Criteria Decision Making (MCDM) methods. This study aims to select the best maintenance strategy for a manufacturing company by using an integrated approach based on fuzzy PIPRECIA and fuzzy MOORA from MCDM methods. Fuzzy extensions of the methods are used because this problem involves uncertainties and difficulties in evaluating alternatives and criteria in precise terms.

The PIPRECIA method is an extension of the SWARA (Stepwise Weight Assessment Ratio Analysis). According to Stanujkic et al. (2017), the SWARA method has some difficulties, such as ranking the criteria in order of importance when there are a lot of criteria and decision-makers. The PIPRECIA method allows the criteria to be evaluated without ranking them according to their importance and gives successful results (Arman and Kundakcı, 2022). Therefore, the PIPRECIA method has an advantage over other MCDM methods in cases where the number of decision-makers is high. The fuzzy PIPRECIA method, which was developed by incorporating fuzzy sets into the classical PIPRECIA method, gives better results than the classical PIPRECIA in cases where the criteria are qualitative or uncertain. For this reason, in this study criteria weights were obtained by the fuzzy PIPRECIA method, which is one of the current MCDM methods. Later fuzzy MOORA method is used to rank and select the best maintenance strategy. The reason why the Fuzzy MOORA method was preferred is that it is simple, robust and does not require complex calculations, and requires a relatively short computation time (Karande & Chakraborty, 2012).

The main contribution of this study is combining fuzzy PIPRECIA and fuzzy MOORA methods for maintenance strategy selection. When the literature was examined, no study has been found that used these two methods applied together. This is the first study in this respect. On the other hand, these two methods have not been used for maintenance strategy selection before. For these reasons, this study will contribute to the literature and researchers that want to determine the best maintenance strategy.

The rest of this study is organized into six sections. In Section 2, a literature review of maintenance strategy selection is presented. Section 3 briefly defines fuzzy sets and fuzzy numbers. Solution methods, Fuzzy PIPRECIA, and fuzzy MOORA methods are introduced, and their steps are given in Section 4. The application of the proposed integrated approach in a manufacturing company is presented in Section 5. In the end, in Section 6, the conclusion, contribution, managerial implication, limitations, and future scope of the study are discussed.

2. LITERATURE REVIEW

In the literature, the maintenance strategy selection process was handled with different methods. Almedia & Bohoris (1995) developed a maintenance decision model and demonstrated the applicability of the model by solving the maintenance strategy problem of a power generation company. Triantaphyllou et al. (1997) proposed the MCDM approach for maintenance selection and discussed sensitivity analysis methodology on the decision criteria of maintenance decision-making. Azadivar & Shu (1999) discussed the selection of maintenance policy for Just-in-Time production systems. They explored characteristic factors of Just-in-Time systems that have a crucial role in selecting an appropriate maintenance policy. Bevilacqua & Braglia (2000) evaluated; preventive, predictive, condition-based, corrective, and opportunistic maintenance strategy alternatives and selected the best strategy for an Italian oil refinery with the AHP method. Mechefske & Wang (2001) proposed to use of fuzzy linguistics for the selection of optimum maintenance strategy. Al-Najjar & Alsyouf (2003) used fuzzy MCDM methods to determine the best maintenance strategy. Bertolini & Bevilacqua (2006) developed a combined approach based on Lexicographic Goal Programming and AHP to determine the most efficient maintenance strategy for centrifugal pumps of an oil refinery. Wang et al. (2007) selected the optimum maintenance strategy by using the fuzzy AHP method. They applied the proposed approach in a power plant and their results indicate that the predictive maintenance strategy is optimal for the plant. Ierace & Cavalieri (2008) used AHP and fuzzy MCDM methods for the selection of the best maintenance strategy in an Italian manufacturing firm. Jafari et al. (2008) proposed a new method that combines fuzzy Delphi and SAW (Simple Additive Weighting) for the solution of the maintenance strategy selection problem. Pariazar et al. (2008) used an integrated approach based on factor analysis and improved AHP that uses rough set theory for the selection of optimum maintenance strategy. Cheng & Tsao (2010) used ANP (Analytic Network Process) method to select a maintenance strategy for rolling stock. They also tried to estimate spare part quantities and replacement intervals of the rolling stock components. Zhaoyang et al. (2011) evaluated maintenance strategy with the risk-based inspection. They applied the AHP method for selecting the best maintenance strategy for equipment in every risk rating scale. Momeni et al. (2011) used the fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method for determining the best maintenance strategy for Electrofan company and as a result, the preventive maintenance strategy has been selected. Bashiri et al. (2011) proposed a new fuzzy linear assignment method to select the optimum maintenance strategy which allows qualitative and quantitative data to be considered together. Zaim et al. (2012) selected the optimal maintenance strategy for a local newspaper printing facility with AHP and ANP methods. Görener (2013) proposed fuzzy WSA (Weighted Sum Approach) and TOPSIS to evaluate maintenance strategy alternatives and select the most appropriate one for a manufacturing plant. Their results indicate that preventive maintenance strategy is selected. Tuyet et al. (2018) aimed to minimize the maintenance cost of the offshore wind system and for this reason, they determine the optimal maintenance schedules. They proposed to use a dynamic maintenance strategy and grouping maintenance optimization strategy. Their results showed a reduction in maintenance cost compared to the baseline maintenance schedule. Emovon et al. (2018) proposed two hybrid approaches based on Delphi-AHP and Delphi-AHP-PROMETHEE methods to select an appropriate maintenance strategy for ship machinery systems. Ighravwe & Oke (2020) proposed an integrated approach based on fuzzy axiomatic design (FAD), fuzzy AHP, and weighted sum & weighted product to select a proactive maintenance strategy for manufacturing systems. Bakhat & Rajaa (2020) proposed a fuzzy hybrid method based on FAHP, and WASPAS-F to select a maintenance strategy for macro systems. Jiménez et al. (2021) proposed an ontology model to select a maintenance strategy. This model helps decision-makers to assess and select maintenance strategies by developing smart computational agents. Arjomandi et al. (2021) proposed a new MCDM approach based on fuzzy DEMATEL, ANP, and VIKOR to select the best maintenance strategy for safety-critical assets. Carpitella et al. (2021) proposed a hybrid MCDM method based on ANP and ELECTRE III methods for the selection of the best maintenance strategy that fits the requirements of the companies. Lopez & Kolios (2022) used Failure Mode and Effects Analysis (FMEA) to determine the criticality of the failure modes and then selected a risk-based maintenance strategy for wind turbine composite blades. Gholami et al. (2022) suggested using fuzzy AHP for selecting the best maintenance strategy for a building's electrical equipment and especially elevators.

In Table 1, the methods used for maintenance strategy selection in the literature are presented.

Table 1. Methods used for maintenance strategy selection in the literature

Authors	Method
Almedia & Bohoris (1995)	Decision theory
Triantaphyllou et al. (1997)	SAW and AHP
Azadivar & Shu (1999)	Simulation models
Bevilacqua & Braglia (2000)	AHP
Mechefske & Wang (2001)	Fuzzy linguistic approach
Al-Najjar & Alsyouf (2003)	Fuzzy MCDM
Bertolini & Bevilacqua (2006)	Lexicographic Goal programming and AHP
Wang et al. (2007)	Fuzzy AHP
Ierace & Cavalieri (2008)	AHP and fuzzy MCDM methods
Pariazar et al. (2008)	Improved AHP and factor analysis
Jafari et al. (2008)	Fuzzy Delphi method and SAW
Cheng & Tsao (2010)	ANP
Zhaoyang et al. (2011)	AHP
Momeni et al. (2011)	Fuzzy TOPSIS
Bashiri et al. (2011)	Fuzzy interactive linear assignment method
Zaim et al. (2012)	AHP and ANP
Görener (2013)	WSA and TOPSIS
Tuyet et al. (2018)	Mathematical modeling
Emovon et al. (2018)	Delphi-AHP and Delphi-AHP-PROMETHEE
Ighravwe & Oke (2020)	FAD, fuzzy AHP, weighted sum, weighted product
Bakhat & Rajaa (2020)	FAHP, WASPAS-F
Jiménez et al. (2021)	Ontology model
Arjomandi et al. (2021)	Fuzzy DEMATEL, ANP, and VIKOR
Carpitella et al. (2021)	ANP and ELECTRE III
Lopez & Kolios (2022)	FMEA
Gholami et al. (2022)	Fuzzy AHP

A more comprehensive literature review for maintenance strategy selection can be reached by Shafiee (2015) and Patil et al. (2022). Shafiee (2015) made a detailed literature review of the usage of MCDM methods in the maintenance strategy selection process. Patil et al. (2022) reviewed 87 research papers about maintenance strategy selection that are published in peer-reviewed journals since 2012.

After reviewing the literature, it was seen that fuzzy PIPRECIA and fuzzy MOORA methods were not used in the selection of maintenance strategy before. In this study, an integrated fuzzy MCDM is proposed to select the best maintenance strategy. For determining the criteria weights fuzzy PIPRECIA method is used, and the maintenance strategy alternatives are evaluated with the help of the fuzzy MOORA method. By using the integrated method manufacturing companies can determine the optimal maintenance strategy for their facilities.

3. FUZZY SETS AND FUZZY NUMBERS

The fuzzy set concept is a generalization of the set concept based on the grading of an element between zero and one. The fuzzy set was first defined by Zadeh in 1965 as a natural extension of ambiguous logic and deals with problems containing vagueness and uncertainty. A linguistic variable is a variable whose values are words or sentences in a natural or artificial language (Zadeh, 1975).

Fuzzy numbers are a special subset of fuzzy sets. Fuzzy numbers are used to characterize imprecise or approximate numerical quantities (around 10, about 15, about 20, etc.). Types of fuzzy numbers can be classified as triangular fuzzy numbers, trapezoidal fuzzy numbers, sigmoidal fuzzy numbers, etc. It is possible to use different fuzzy numbers depending on the subject, but generally triangular fuzzy numbers (TFNs) are preferred in practical applications due to ease of calculation. In this study, TFNs are used in fuzzy PIPRECIA and MOORA methods. Triangular fuzzy numbers can be defined as (a, b, c). Here a, b, and c, respectively, show the smallest possible value, the most promising value, and the largest possible value which describe a fuzzy event. Triangular fuzzy number $\tilde{A}$'s membership function is given in Equation 1.

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x < a \\ \frac{(x-a)}{(b-a)}, & a \le x < b \\ \frac{(c-x)}{(c-b)}, & b \le x \le c \\ 0, & x > c \end{cases} \tag{1}$$

Let (a_1, b_1, c_1) and (a_2, b_2, c_2) are two positive triangular fuzzy numbers and then operations on fuzzy numbers can be given as follows:

$$(a_1, b_1, c_1) + (a_2, b_2, c_2) = (a_1+a_2, b_1 + b_2, c_1 + c_2) \tag{2}$$

$$(a_1, b_1, c_1) - (a_2, b_2, c_2) = (a_1-c_2, b_1 - b_2, c_1 - a_2) \tag{3}$$

$$(a_1, b_1, c_1).(a_2, b_2, c_2) = (a_1.a_2, b_1.b_2, c_1.c_2) \tag{4}$$

$$k.(a_1, b_1, c_1) .= (k.a_1, k.b_1, k.c_1); \quad k > 0 \text{ and } k \epsilon R \tag{5}$$

$$(a_1, b_1, c_1) / (a_2, b_2, c_2) = (a_1/c_2, b_1/b_2, c_1/a_2) \tag{6}$$

$$(a_1, b_1, c_1)^{-1} = (1/c_1, 1/b_1, 1/a_1) \tag{7}$$

4. SOLUTION METHODS

4.1. Fuzzy PIPRECIA

A crisp form of the PIPRECIA method was proposed by Stanujkić et al. in 2017. Although the PIPRECIA method is based on the extension of the SWARA method, it has some advantages over SWARA. It evaluates the criteria without ranking them in order of importance. Especially in group decision making which involves a large number of decision-makers, the PIPRECIA method has an advantage over other MCDM methods to determine the criteria weights. The PIPRECIA method was first extended to the fuzzy environment by Stević et al. in 2018. They used fuzzy PIPRECIA for the assessment of conditions of information technology implementation in a warehouse system. After the fuzzy PIPRECIA method was proposed, it was applied to different areas in the literature. For instance, Vesković et al. (2020a) used the fuzzy PIPRECIA method to determine the criteria weights of the reach stacker for the container terminal selection problem. Đalić, et al. (2020a) integrated fuzzy PIPRECIA and interval rough SAW model to select a green supplier. Memiş et al. (2020) prioritized the road transportation risk factors by using the fuzzy PIPRECIA method. They reached the result that the transport infrastructure-based risks criterion is the most important, and the risk to be lost and disappearance factor is the least important criterion. Tomašević et al. (2020) evaluated the criteria to implement high-performance computing in Danube Region Countries with the help of fuzzy PIPRECIA. Dobrosavljević et al. (2020) proposed an integrated MCDM approach based on FUCOM (Full Consistency Method) and fuzzy PIPRECIA to evaluate the process orientation dimensions of the apparel industry. Vesković et al. (2020b) integrated fuzzy PIPRECIA and fuzzy EDAS methods for the selection of the best solution for a business balance of passenger rail operators. Jocic et al. (2020) proposed a new integrated approach based on PIPRECIA and an interval-valued triangular fuzzy ARAS approach to select an e-learning course. Blagojević et al. (2020) used a novel Entropy-Fuzzy PIPRECIA-DEA model to evaluate the safety of railway traffic. Đalić et al. (2020b) integrated Swot and Fuzzy PIPRECIA methods to analyze the competitiveness to improve the performance of logistics. Özdağoğlu et al. (2021), determined the criteria weights for the evaluation of the world's busiest airports with the PIPRECIA-E method.

The steps of the fuzzy PIPRECIA method can be given below (Stević et al., 2018):

Step 1. In the first step, the decision makers committee (DM_1, DM_2, …, DM_k) is determined. Then n evaluation criteria are defined by the members of the decision committee.

Step 2. Each decision-maker individually evaluates each criterion by starting from the second one to determine the relative importance of criteria by using Equation 8.

$$\tilde{s}_j^r = \begin{Bmatrix} >\tilde{1} \text{ if } C_j > C_{j-1} \\ =\tilde{1} \text{ if } C_j = C_{j-1} \\ <\tilde{1} \text{ if } C_j < C_{j-1} \end{Bmatrix} \tag{8}$$

$\tilde{s}_j^r$ indicates the assessment of the criteria by the decision maker r. Decision makers used the linguistic variables in Table 2 and Table 3 while evaluating the criteria. Later, $\tilde{s}_j$ matrix is obtained from $\tilde{s}_j^r$ matrix by using geometric mean.

Table 2. Scale 1-2 and Linguistic variables to evaluate the criteria

Linguistic Variables	TFNs for criteria
Almost equal (AE)	(1, 1, 1.05)
Slightly more significant (SMS)	(1.1, 1.15, 1.2)
Moderately more significant (MDMS)	(1.2, 1.3, 1.35)
More significant (MS)	(1.3, 1.45, 1.5)
Much more significant (MMS)	(1.4, 1.6, 1.65)
Dominantly more significant (DMS)	(1.5, 1.75, 1.8)
Absolutely more significant (AMS)	(1.6, 1.9, 1.95)

Table 3. Scale 0-1 and Linguistic variables to evaluate the criteria

Linguistic Variables	TFNs for criteria
Weakly less significant (WLS)	(0.667, 1, 1)
Moderately less significant (MDLS)	(0.5, 0.667, 1)
Less significant (LS)	(0.4, 0.5, 0.667)
Really less significant (RLS)	(0.333, 0.4, 0.5)
Much less significant (MLS)	(0.286, 0.333, 0.4)
Dominantly less significant (DLS)	(0.25, 0.286, 0.333)
Absolutely less significant (ALS)	(0.222, 0.25, 0.286)

Step 3. Coefficient $\tilde{k}_j$ is determined with the help of Equation 9.

$$\tilde{k}_j=\begin{Bmatrix} \tilde{1} & \text{if} & j=1 \\ 2\text{-}\tilde{s}_j & \text{if} & j>1 \end{Bmatrix} \tag{9}$$

Step 4. Fuzzy weight $\tilde{q}_j$ is calculated via Equation 10.

$$\tilde{q}_j=\begin{Bmatrix} \tilde{1} & \text{if} & j=1 \\ \frac{\tilde{q}_{j-1}}{\tilde{k}_j} & \text{if} & j>1 \end{Bmatrix} \tag{10}$$

Step 5. Relative weight $\tilde{w}_j$ is determined by using Equation 11.

$$\tilde{w}_j=\frac{\tilde{q}_j}{\sum_{j=1}^{n}\tilde{q}_j} \tag{11}$$

The following steps indicate the inverse methodology of the fuzzy PIPRECIA method.

Step 6. Starting from the penultimate criterion, the evaluations between the criteria are made by decision-makers using the linguistic variables given in Table 2 and Table 3.

$$\tilde{s}_{j'}^{r}=\begin{Bmatrix} >\tilde{1} \text{ if } C_j>C_{j-1} \\ =\tilde{1} \text{ if } C_j=C_{j-1} \\ <\tilde{1} \text{ if } C_j<C_{j-1} \end{Bmatrix} \quad (12)$$

$\tilde{s}_{j'}^{r}$ indicates the assessment of criteria by a decision maker *r*. Similarly for the inverse PIPRECIA, it is necessary to obtain the average $\tilde{s}_{j'}^{r}$ matrix by using geometric mean.

Step 7. Coefficient $\tilde{k}_{j'}$ is determined by using Equation 13.

$$\tilde{k}_{j'}=\begin{Bmatrix} \tilde{1} & \text{if } j=n \\ 2-\tilde{s}_{j'} & \text{if } j>n \end{Bmatrix} \quad (13)$$

Here *n* indicates the number of criteria.

Step 8. Fuzzy weight $\tilde{q}_{j'}$ is calculated with the help of Equation 14.

$$\tilde{q}_{j'}=\begin{Bmatrix} \tilde{1} & \text{if } j=n \\ \dfrac{\tilde{q}_{j-1'}}{\tilde{k}_{j'}} & \text{if } j>n \end{Bmatrix} \quad (14)$$

Step 9. Relative weights of the criteria $\tilde{w}_{j'}$ are obtained by using Equation 15.

$$\tilde{w}_{j'}=\frac{\tilde{q}_{j'}}{\sum_{j=1}^{n}\tilde{q}_{j'}} \quad (15)$$

Step 10. The final criteria weights $\tilde{w}_{j''}$ are obtained via Equation 16.

$$\tilde{w}_{j''}=\frac{1}{2}(\tilde{w}_j+\tilde{w}_{j'}) \quad (16)$$

Step 11. Finally, the consistencies of the results obtained from the fuzzy PIPRECIA and inverse fuzzy PIPRECIA methods are checked with the Spearman and Pearson correlation coefficients.

4.2. Fuzzy MOORA

Multi-Objective Optimization on the basis of Ratio Analysis (MOORA) optimizes simultaneously two or more conflicting objectives, subject to certain constraints (Dey et al., 2012). Brauers & Zavadskas first proposed MOORA in 2006. Then its fuzzy extension was proposed by Karande & Chakraborty in 2012. Later, fuzzy MOORA has been proposed to solve different MCDM problems in the literature. Fuzzy MOORA has been used for solving MCDM problems (Archana & Sujatha, 2012), personnel selection (Baležentis et al., 2012), supply chain strategy selection (Dey et al., 2012) selection of the best intelligent manufacturing system (Mandal & Sarkar, 2012), industrial engineering sector choosing (Akkaya et al., 2015), supplier selection (Pérez-Domínguez et al., 2015; Matawale et al., 2016; Arabsheybani et al., 2018; Bera et al., 2020), selecting sustainable third-party reverse logistic provider (Mavi et al., 2017), course selection (Ersöz et al., 2018), an automated hammering machine design and fabrication (Emovon et al., 2021), selecting solar plant location (Khorshidi et al. 2022).

The steps of the fuzzy MOORA are given below (Karande & Chakraborty, 2012):

Step 1. The decision committee which consists of decision makers (DM_1, DM_2, …, DM_k) determines m alternatives and n evaluation criteria. Alternatives are evaluated by using the linguistic variables expressed in terms of fuzzy triangular numbers given in Table 4 (Chen, 2000). Then, criteria weights are determined. In this study, the fuzzy PIPRECIA method is proposed to determine these weights.

Table 4. Linguistic variables to evaluate alternatives

Linguistic Variables	TFNs for alternatives
Very Low (VL)	(0, 0, 1)
Low (L)	(0, 1, 3)
Medium Low (ML)	(1, 3, 5)
Medium (M)	(3, 5, 7)
Medium High (MH)	(5, 7, 9)
High (H)	(7, 9, 10)
Very High (VH)	(9, 10, 10)

Step 2. For reducing the evaluations of the decision makers for alternatives into a single value, Equation 17 is used.

$$\tilde{x}_{ij} = \frac{1}{k}\left[\tilde{x}_{ij}^{1} + \tilde{x}_{ij}^{2} + \cdots + \tilde{x}_{ij}^{k}\right] \tag{17}$$

Here, $\tilde{x}_{ij}^{k}$ indicates the evaluation of decision maker k for ith (i=1,…,m) alternative under jth (j=1,…,n) criterion.

Step 3. Fuzzy decision matrix $\tilde{D}$ and fuzzy weight vector are obtained as given in Equation 18. In this study, a fuzzy weight vector is obtained with the fuzzy PIPRECIA method.

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \cdots & \tilde{x}_{mn} \end{bmatrix} \qquad \tilde{w} = [\tilde{w}_1, \tilde{w}_2, \ldots, \tilde{w}_n] \tag{18}$$

In this matrix $\tilde{x}_{ij} = (x_{ij}^{l},\ x_{ij}^{m},\ x_{ij}^{u})$ and $x_{ij}^{l},\ x_{ij}^{m},\ x_{ij}^{u}$ denote the lower, middle, and upper values of triangular fuzzy number $\tilde{x}_{ij}$.

Step 4. The normalized fuzzy decision matrix $\tilde{R}$ given in Equation 19 is formed using Equations between 20 and 22.

$$\tilde{R} = [\tilde{r}_{ij}]_{mxn} \tag{19}$$

Here $\tilde{r}_{ij} = (r_{ij}^{l},\ r_{ij}^{m},\ r_{ij}^{u})$ and these values are obtained via Equations 20, 21, and 22 respectively.

$$r_{ij}^{l} = \frac{x_{ij}^{l}}{\sqrt{\sum_{i=1}^{m}\left[\left(x_{ij}^{l}\right)^2 + \left(x_{ij}^{m}\right)^2 + \left(x_{ij}^{u}\right)^2\right]}} \tag{20}$$

$$r_{ij}^{m} = \frac{x_{ij}^{m}}{\sqrt{\sum_{i=1}^{m}\left[\left(x_{ij}^{l}\right)^{2} + \left(x_{ij}^{m}\right)^{2} + \left(x_{ij}^{u}\right)^{2}\right]}} \tag{21}$$

$$r_{ij}^{u} = \frac{x_{ij}^{u}}{\sqrt{\sum_{i=1}^{m}\left[\left(x_{ij}^{l}\right)^{2} + \left(x_{ij}^{m}\right)^{2} + \left(x_{ij}^{u}\right)^{2}\right]}} \tag{22}$$

Step 5. Weighted normalized decision matrix $\tilde{V}$ is determined with the help of Equation 23.

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{mxn} \tag{23}$$

Here, $\tilde{v}_{ij} = \tilde{r}_{ij}.\tilde{w}_j$ and $\tilde{v}_{ij} = (v_{ij}^{l},\ v_{ij}^{m},\ v_{ij}^{u})$.

Step 6. For each alternative, overall ratings of benefit and cost criteria are determined.

For benefit criteria, the overall ratings of an alternative for lower, middle, and upper values are calculated by using Equations. 24, 25, and 26 respectively.

$$s_i^{+l} = \sum_{j=1}^{n} v_{ij}^{l} \,\Big|\, j \in J^{\max} \tag{24}$$

$$s_i^{+m} = \sum_{j=1}^{n} v_{ij}^{m} \,\Big|\, j \in J^{\max} \tag{25}$$

$$s_i^{+u} = \sum_{j=1}^{n} v_{ij}^{u} \,\Big|\, j \in J^{\max} \tag{26}$$

For cost criteria, the overall ratings of an alternative for lower, middle, and upper values are calculated by using Equations 27, 28, and 29 respectively.

$$s_i^{-l} = \sum_{j=1}^{n} v_{ij}^{l} \,\Big|\, j \in J^{\min} \tag{27}$$

$$s_i^{-m} = \sum_{j=1}^{n} v_{ij}^{m} \,\Big|\, j \in J^{\min} \tag{28}$$

$$s_i^{-u} = \sum_{j=1}^{n} v_{ij}^{u} \,\Big|\, j \in J^{\min} \tag{29}$$

Step 7. Each alternative's overall performance index (*Si*) is determined. The Vertex method (Chen, 2000) is used to calculate defuzzified values of the overall ratings for benefit and cost criteria for each alternative as seen in Equation 30.

$$S_i\left(s_i^{+}, s_i^{-}\right) = \sqrt{\frac{1}{3}\left[\left(s_i^{+l} - s_i^{-l}\right)^{2} + \left(s_i^{+m} - s_i^{-m}\right)^{2} + \left(s_i^{+u} - s_i^{-u}\right)^{2}\right]} \tag{30}$$

Step 8. Finally, the ranking of the alternatives is determined based on their overall performance index values. The alternative with the highest overall performance index is the best one.

5. APPLICATION

A manufacturing company operating in Denizli, Turkey wants to select the best strategy for its company. In maintenance management systems, there are different strategies according to the sector in which the business operates. These strategies are grouped into four groups, and they are considered as alternatives: A_1 Corrective maintenance (CM), A_2 Preventive Time-based maintenance (PTBM), A_3 Condition-based maintenance (CBM), and A_4 Predictive maintenance (PDM). Then decision-makers determined eight criteria to be used in the evaluation of four maintenance strategies. These criteria can be given as;

- C_1 Safety of facility and equipment,
- C_2 Safety of personnel,
- C_3 Safety of environment,
- C_4 Acceptance by labors,
- C_5 Equipment, and technology capability,
- C_6 Added value to product quality,
- C_7 Added value for equipment and personnel efficiency,
- C_8 Personnel training cost.

To handle the maintenance strategy selection problem of the manufacturing company a combined fuzzy MCDM approach has been proposed. This approach is composed of four main stages. In the first stage, decision-makers are determined, and data are gathered. In the second stage, criteria weights are determined with fuzzy PIPRECIA and in the third stage, alternatives are evaluated with fuzzy MOORA method. In the end, in stage 4 final decision has been made and the best alternative is selected. The steps of the proposed method are summarized in Figure 1.

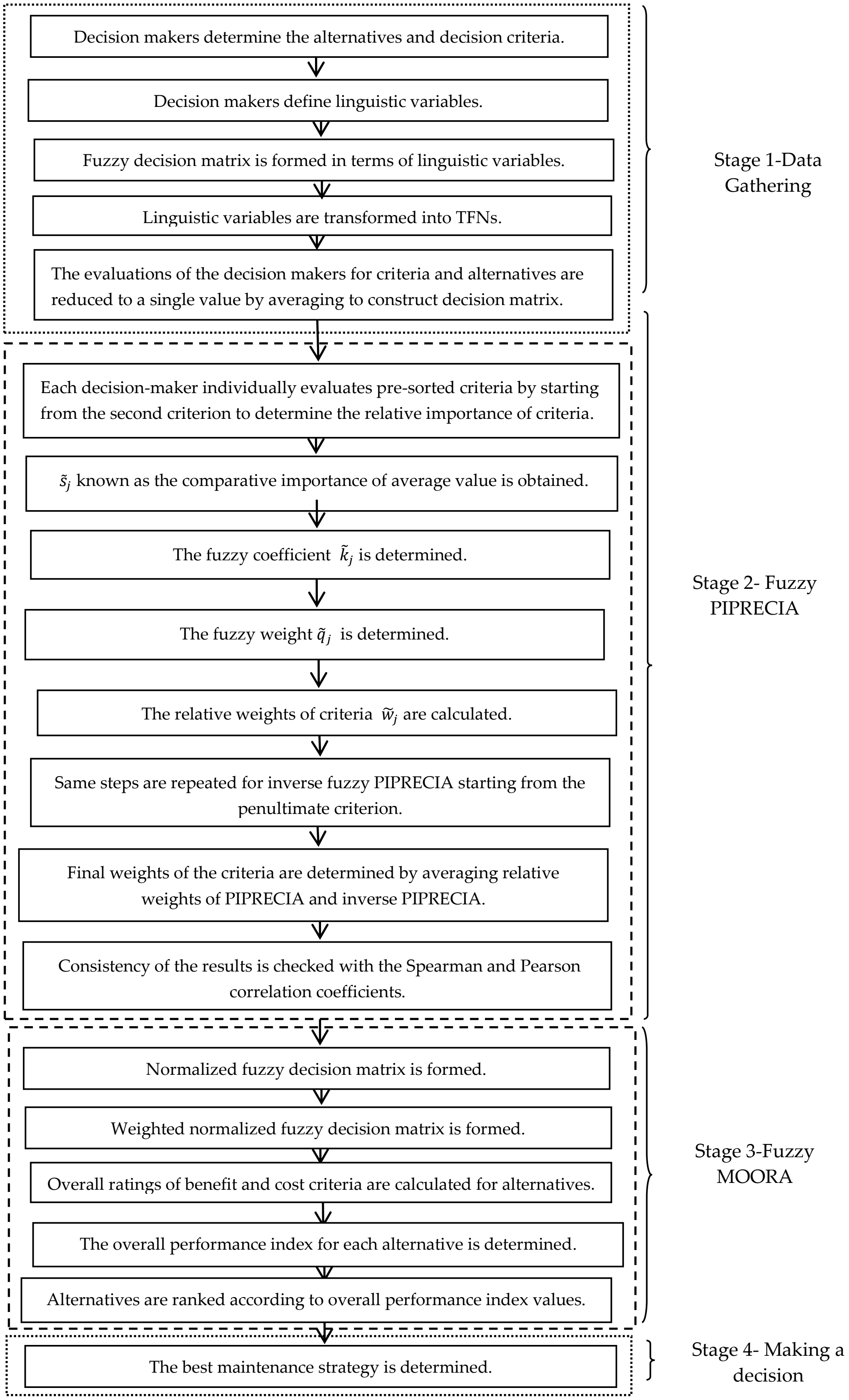

Figure 1. Flowchart of the integrated fuzzy MCDM approach

The criteria weights are determined with the help of fuzzy PIPRECIA. All decision-makers individually evaluate the criteria by starting from the second criterion to determine the relative importance of criteria by using Equation 8. Decision-makers used the linguistic variables in Table 2 and Table 3 while evaluating the criteria. These evaluation results for criteria with fuzzy PIPRECIA are given in Table 5 and inverse fuzzy PIPRECIA are given in Table 6.

Table 5. Evaluation of criteria by decision makers with fuzzy PIPRECIA method

PIPRECIA	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
DM_1		SMS	LS	WLS	WLS	MS	SMS	LS
DM_2		MDMS	RLS	MDLS	WLS	MMS	SMS	LS
DM_3		SMS	RLS	MDLS	MDLS	MS	SMS	MDLS

Table 6. Evaluation of criteria by decision makers with inverse fuzzy PIPRECIA method

PIPRECIA I	C_8	C_7	C_6	C_5	C_4	C_3	C_2	C_1
DM_1		MDMS	MDLS	RLS	AE	SMS	MDMS	MDLS
DM_2		MDMS	MDLS	MLS	AE	SMS	MS	LS
DM_3		SMS	MDLS	RLS	SMS	AE	MS	MDLS

Later evaluations of decision makers in terms of linguistic variables are transformed to triangular fuzzy numbers equivalent given in Table 2 and Table 3. In this way, $\tilde{s}_j^r$ values are obtained, and they indicate the assessment of the criteria by the decision maker r. These transformed forms of evaluations are given in Table 7 for fuzzy PIPRECIA and in Table 8 for inverse fuzzy PIPRECIA.

Table 7. Evaluations of decision-makers in terms of TFNs for the fuzzy PIPRECIA method

P	C_1			C_2			C_3			C_4		
DM_1				(1.10,	1.15,	1.20)	(0.40,	0.50,	0.67)	(0.67,	1.00,	1.00)
DM_2				(1.20,	1.30,	1.35)	(0.33,	0.40,	0.50)	(0.50,	0.67,	1.00)
DM_3				(1.10,	1.15,	1.20)	(0.33,	0.40,	0.50)	(0.50,	0.67,	1.00)
	C_5			C_6			C_7			C_8		
DM_1	(0.67,	1.00,	1.00)	(1.30,	1.45,	1.50)	(1.10,	1.15,	1.20)	(0.40,	0.50,	0.67)
DM_2	(0.67,	1.00,	1.00)	(1.40,	1.60,	1.65)	(1.10,	1.15,	1.20)	(0.40,	0.50,	0.67)
DM_3	(0.50,	0.67,	1.00)	(1.30,	1.45,	1.50)	(1.10,	1.15,	1.20)	(0.50,	0.67,	1.00)

Table 8. Evaluations of decision makers for inverse fuzzy PIPRECIA method

P-I	C_8			C_7			C_6			C_5		
DM_1				(1.20,	1.30,	1.35)	(0.50,	0.67,	1.00)	(0.33,	0.40,	0.50)
DM_2				(1.20,	1.30,	1.35)	(0.50,	0.67,	1.00)	(0.29,	0.33,	0.40)
DM_3				(1.10,	1.15,	1.20)	(0.50,	0.67,	1.00)	(0.33,	0.40,	0.50)
	C_4			C_3			C_2			C_1		
DM_1	(1.00,	1.00,	1.05)	(1.10,	1.15,	1.20)	(1.20,	1.30,	1.35)	(0.50,	0.67,	1.00)
DM_2	(1.00,	1.00,	1.05)	(1.10,	1.15,	1.20)	(1.30,	1.45,	1.50)	(0.40,	0.50,	0.67)
DM_3	(1.10,	1.15,	1.20)	(1.00,	1.00,	1.05)	(1.30,	1.45,	1.50)	(0.50,	0.67,	1.00)

Later, $\tilde{s}_j$ matrix is obtained from $\tilde{s}_j^r$ matrix by using geometric mean. $\tilde{s}_j$ values are given in the first column of Table 9. Then $\tilde{k}_j$ is determined with the help of Equation 9. Fuzzy weight $\tilde{q}_j$ is calculated via Equation 10. At the end relative weight $\tilde{w}_j$ is determined by using Equation 11. These values are presented in Table 9. All these computations have been done for inverse fuzzy PIPRECIA and solutions are given in Table 10.

Table 9. Results of fuzzy PIPRECIA

	$\tilde{s}_j$	$\tilde{k}_j$	$\tilde{q}_j$	$\tilde{w}_j$
C1		(1.000, 1.000, 1.000)	(1.000, 1.000, 1.000)	(0.085, 0.131, 0.194)
C2	(1.132, 1.198, 1.248)	(0.752, 0.802, 0.868)	(1.153, 1.247, 1.330)	(0.098, 0.163, 0.258)
C3	(0.354, 0.431, 0.550)	(1.450, 1.569, 1.646)	(0.700, 0.795, 0.917)	(0.060, 0.104, 0.178)
C4	(0.550, 0.763, 1.000)	(1.000, 1.237, 1.450)	(0.483, 0.643, 0.917)	(0.041, 0.084, 0.178)
C5	(0.606, 0.874, 1.000)	(1.000, 1.126, 1.394)	(0.346, 0.571, 0.917)	(0.030, 0.075, 0.178)
C6	(1.333, 1.498, 1.548)	(0.452, 0.502, 0.667)	(0.519, 1.137, 2.032)	(0.044, 0.149, 0.395)
C7	(1.100, 1.150, 1.200)	(0.800, 0.850, 0.900)	(0.577, 1.338, 2.539)	(0.049, 0.175, 0.494)
C8	(0.431, 0.550, 0.763)	(1.237, 1.450, 1.569)	(0.368, 0.923, 2.054)	(0.031, 0.121, 0.399)

Table 10. Results of Inverse fuzzy PIPRECIA

	$\tilde{s}_j$	$\tilde{k}_j$	$\tilde{q}_j$	$\tilde{w}_j$
C1	(0.464, 0.606, 0.874)	(1.126, 1.394, 1.536)	(0.466, 0.852, 1.941)	(0.042, 0.116, 0.342)
C2	(1.266, 1.398, 1.448)	(0.552, 0.602, 0.734)	(0.715, 1.188, 2.186)	(0.064, 0.162, 0.386)
C3	(1.066, 1.098, 1.148)	(0.852, 0.902, 0.934)	(0.525, 0.715, 1.206)	(0.047, 0.097, 0.213)
C4	(1.032, 1.048, 1.098)	(0.902, 0.952, 0.968)	(0.490, 0.645, 1,028)	(0.044, 0.088, 0.181)
C5	(0.317, 0.376, 0.464)	(1.536, 1.624, 1.683)	(0.475, 0.614, 0.928)	(0.043, 0.084, 0.164)
C6	(0.500, 0.667, 1.000)	(1.000, 1.333, 1.500)	(0.799, 0.998, 1.425)	(0.072, 0.136, 0.251)
C7	(1.166, 1.248, 1.298)	(0.702, 0.752, 0.834)	(1.199, 1.330, 1.425)	(0.108, 0.181, 0.251)
C8		(1.000, 1.000, 1.000)	(1.000, 1.000, 1.000)	(0.090, 0.136, 0.176)

The consistency of the results obtained from the fuzzy PIPRECIA and inverse fuzzy PIPRECIA methods is checked with the Spearman and Pearson correlation coefficients. They were obtained as 0,904 and 0.929 respectively. In the end, the final criteria weights are obtained via Equation 16 as seen in Table 11.

Table 11. Final weights of criteria

	PIPRECIA $\tilde{w}_j$	**I-PIPRECIA $\tilde{w}_j$**	**Final Weights**
C1	(0.085, 0.131, 0.194)	(0.042, 0.116, 0.342)	(0.064, 0.123, 0.268)
C2	(0.098, 0.163, 0.258)	(0.064, 0.162, 0.386)	(0.081, 0.162, 0.322)
C3	(0.060, 0.104, 0.178)	(0.047, 0.097, 0.213)	(0.053, 0.101, 0.196)
C4	(0.041, 0.084, 0.178)	(0.044, 0.088, 0.181)	(0.043, 0.086, 0.180)
C5	(0.030, 0.075, 0.178)	(0.043, 0.084, 0.164)	(0.036, 0.079, 0.171)
C6	(0.044, 0.149, 0.395)	(0.072, 0.136, 0.251)	(0.058, 0.142, 0.323)
C7	(0.049, 0.175, 0.494)	(0.108, 0.181, 0.251)	(0.078, 0.178, 0.372)
C8	(0.031, 0.121, 0.399)	(0.090, 0.136, 0.176)	(0.061, 0.128, 0.288)

After the weights of the criteria are obtained by using the fuzzy PIPRECIA method, the ranking of the alternatives is determined with the help of the fuzzy MOORA method. According to the Fuzzy MOORA method, firstly alternatives are evaluated by three decision-makers by using the linguistic variables given in Table 4.

Table 12. Evaluation of alternatives under each criterion by decision-makers

Criteria	Alternatives	Decision Makers		
		DM_1	DM_2	DM_3
C_1 Safety of facility and equipment	A_1	L	ML	M
	A_2	M	M	ML
	A_3	MH	H	M
	A_4	H	VH	H
C_2 Safety of personnel	A_1	L	M	ML
	A_2	MH	MH	M
	A_3	MH	H	MH
	A_4	H	VH	H
C_3 Safety of the environment	A_1	ML	M	L
	A_2	M	MH	ML
	A_3	MH	H	MH
	A_4	MH	H	H
C_4 Acceptance by labors	A_1	H	MH	H
	A_2	MH	M	M
	A_3	ML	ML	L
	A_4	M	M	MH
C_5 Equipment and technology capability	A_1	L	ML	M
	A_2	ML	M	H
	A_3	M	MH	MH
	A_4	VH	H	H
C_6 Added value to product quality	A_1	L	ML	ML
	A_2	MH	H	MH
	A_3	M	H	MH
	A_4	H	VH	H
C_7 Added value for equipment and personnel efficiency	A_1	VL	L	ML
	A_2	M	MH	M
	A_3	MH	H	MH
	A_4	H	VH	H
C_8 Personnel training cost	A_1	L	ML	M
	A_2	ML	M	MH
	A_3	H	MH	H
	A_4	M	ML	M

Decision makers' evaluations for alternatives are reduced to a single value via Equation 17. Later, a fuzzy decision matrix is constructed as given in Table 13.

Table 13. Fuzzy decision matrix

	A1	**A2**	**A3**	**A4**
C1	(1.33, 3, 5)	(2.33, 4.33, 6.33)	(5, 7, 8.67)	(7.67, 9.33, 10)
C2	(1.33, 3, 5)	(4,33, 6.33, 8.33)	(5.67, 7.67, 9.33)	(7.67, 9.33, 10)
C3	(1.33, 3, 5)	(3, 5, 7)	(5.67, 7.67, 9.33)	(6.33, 8.33, 9.67)
C4	(6.33, 8.33, 9.67)	(3.67, 5.67, 7.67)	(0.67, 2.33, 4.33)	(3.67, 5.67, 7.67)
C5	(1.33, 3, 5)	(3.67, 5.67, 7.33)	(4.33, 6.33, 8.33)	(7.67, 9.33, 10)
C6	(0.67, 2.33, 4.33)	(5.67, 7.67, 9.33)	(5, 7, 8.67)	(7.67, 9.33,10)
C7	(0.33, 1.33, 3)	(3.67, 5.67, 7.67)	(5.67, 7.67, 9.33)	(7.67, 9.33, 10)
C8	(7.67, 9.33, 10)	(3.67, 5.67, 7.67)	(6.33, 8.33, 9.67)	(6.33, 8.33, 9.67)

Then, the normalized fuzzy decision matrix is constructed as given in Table 14. The values of this matrix are obtained with the help of Equations 20, 21, and 22.

Table 14. Normalized fuzzy decision matrix

	A1	**A2**	**A3**	**A4**
C1	(0.06, 0.13, 0.22)	(0.10, 0.19, 0.28)	(0.22, 0.31, 0.39)	(0.34, 0.42, 0.45)
C2	(0.05, 0.12, 0.21)	(0.18, 0.26, 0.34)	(0.23, 0.32, 0.38)	(0.32, 0.38, 0.41)
C3	(0.06, 0.13, 0.22)	(0.13, 0.22, 0.31)	(0.25, 0.34, 0.42)	(0.28, 0.37, 0.43)
C4	(0.30, 0.40, 0.46)	(0.18, 0.27, 0.37)	(0.03, 0.11, 0.21)	(0.18, 0.27, 0.37)
C5	(0.06, 0.13, 0.22)	(0.16, 0.25, 0.32)	(0.19, 0.28, 0.37)	(0.34, 0.41, 0.44)
C6	(0.03, 0.10, 0.18)	(0.23, 0.31, 0.38)	(0.20, 0.29, 0.35)	(0.31, 0.38, 0.41)
C7	(0.01, 0.06, 0.13)	(0.16, 0.24, 0.33)	(0.24, 0.33, 0.40)	(0.33, 0.40, 0.43)
C8	(0.28, 0.34, 0.36)	(0.13, 0.21, 0.28)	(0.23, 0.30, 0.35)	(0.23, 0.30, 0.35)

Later, the weighted normalized decision matrix is constructed by using Equation 23 as seen in Table 15.

Table 15. Weighted normalized fuzzy decision matrix

	A1	**A2**	**A3**	**A4**
C1	(0.004, 0.017, 0.060)	(0.007, 0.024, 0.076)	(0.014, 0.039, 0.104)	(0.022, 0.052, 0.120)
C2	(0.004, 0.020, 0.066)	(0.014, 0.042 0.111)	(0.019, 0.051, 0.124)	(0.026, 0.062, 0.133)
C3	(0.003, 0.014, 0.044)	(0.007, 0.023, 0.061)	(0.013, 0.035, 0.082)	(0.015, 0.038, 0.085)
C4	(0.013, 0.034, 0.083)	(0.008, 0.023, 0.066)	(0.001, 0.010, 0.037)	(0.008, 0.023, 0.066)
C5	(0.002, 0.011, 0.038)	(0.006, 0.020, 0.056)	(0.007, 0.022, 0.063)	(0.012, 0.033, 0.076)
C6	(0.002, 0.014, 0.057)	(0.013, 0.045, 0.123)	(0.012, 0.041, 0.115)	(0.018, 0.054, 0.132)
C7	(0.001, 0.010, 0.048)	(0.012, 0.043, 0.123)	(0.019, 0.059, 0.150)	(0.026, 0.072, 0.160)
C8	(0.017, 0.044, 0.105)	(0.008, 0.026, 0.080)	(0.014, 0.039, 0.101)	(0.014, 0.039, 0.101)

In the end, each alternative's overall ratings of benefit and cost criteria are calculated. For benefit criteria, Equations 24, 25, and 26 are used, whereas the overall ratings of an alternative for cost criteria are obtained by using Equations 27, 28, and 29. Then, the overall performance index (S_i) for each alternative is determined with the help of Equation 30. All these values are given in Table 16.

Table 16. Overall ratings of benefit and cost criteria and overall performance index

	s_i^+	s_i^-	s_i
A_1	(0.029, 0.119, 0.397)	(0.017, 0.044, 0.105)	0.174
A_2	(0.068, 0.220, 0.616)	(0.008, 0.026, 0.080)	0.331
A_3	(0.086, 0.256, 0.675)	(0.014, 0.039, 0.101)	0.357
A_4	(0.127, 0.333, 0.772)	(0.014, 0.039, 0.101)	0.428

The ranking of alternatives is determined according to their overall performance index values as $A_4 > A_3 > A_2 > A_1$.

5. CONCLUSION

In recent years, increased competition forces manufacturers to give more importance to their facilities, equipment, and machinery. Therefore, businesses need to determine the most appropriate and cost-effective maintenance strategy for their production facilities.

Since it is difficult to clearly express the criteria and alternatives in the evaluation process of maintenance strategy alternatives with numerical values, fuzzy PIPRECIA and MOORA methods, in which linguistic variables are used, have been proposed to evaluate the criteria and alternatives. Four maintenance strategies and eight criteria were taken into consideration for the application of the proposed model. The result of the proposed integrated approach indicates that the ranking of the maintenance strategies was $A_4 > A_3 > A_2 > A_1$ and the predictive maintenance strategy was determined as the most appropriate maintenance strategy. Therefore, the company was advised to choose the predictive maintenance strategy to achieve company goals such as improving product quality and productivity and reducing cost and machine downtime. Moreover, it was suggested that they should determine their maintenance plans based on historical and technical data on equipment or machine failures. The obtained results of the application indicate that this integrated approach could be applied within other industries and facilities.

There are many studies have been published on maintenance strategy selection. However, none of the existing studies have suggested using fuzzy PIPRECIA and fuzzy MOORA methods. After a comprehensive literature review, this combination of methods appears to have been proposed for the first time to select the best maintenance strategy. Furthermore, the proposed integrated fuzzy MCDM approach could be useful for future research in different fields due to its applicability and simplicity.

The proposed approach can assist managers in evaluating maintenance strategies and selecting the best one for the manufacturing company. Selecting the best maintenance strategy provides the company to increase product quality, plant safety, and efficiency and to decrease manufacturing costs. Moreover, the integrated approach presents a structured way to select the most appropriate maintenance strategy based on the company's needs.

The first limitation of this study is that the results obtained are based on an application in a manufacturing company and they cannot be generalized. Since the proposed approach is based on the concept of fuzzy set and expert knowledge, the results obtained are affected by this situation. The experience and knowledge of the experts will directly affect the quality of the decision taken. This constitutes another limitation of the study.

In future studies, Total Productive Maintenance (TPM) strategy, which is the process of maximizing equipment effectiveness through the active involvement of all supporting departments rather than just the maintenance team, can be evaluated as another alternative strategy for the manufacturing company. On the other hand, the maintenance strategy selection problem can be solved with other fuzzy MCDM methods, and the results can be compared. Furthermore, sensitivity analysis can be performed, and the reliability of the results can be tested. In addition, the integrated fuzzy MCDM method can be applied to different selection problems of the manufacturing company.

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