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RESEARCH ARTICLE

A NEW HYBRID MODEL PROPOSAL FOR FMEA ANALYSIS WITH FUZZY MULTI-CRITERIA DECISION-MAKING TECHNIQUES

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Abstract

Businesses apply various strategies to increase customer satisfaction and to get ahead of their competitors in the market. One of the methods used within the framework of this strategy is the Failure Mode and Effects Analysis (FMEA) method, which enables the discovery of failures in products or services before they occur. In the FMEA method, the severity, likelihood, and detection of potential failures are determined and scored. However, it is possible to state that the FMEA method may be insufficient in cases where more sensitive analysis is required due to the limited nature of the measures used in the scoring process. To prevent this, a hybrid study was conducted in which a new ranking was made using classical FMEA and multiple fuzzy multi-criteria decision-making techniques. Upon reviewing the literature, no FMEA studies using more than two multi-criteria decision-making techniques have been found. Therefore, alongside a standard FMEA study, a separate standard FMEA study was conducted using fuzzy TOPSIS, fuzzy VIKOR, fuzzy GRAY Relational Analysis, and fuzzy MOORA methods, which were randomly selected and weighted using DEMATEL. Subsequently, a new ranking was created by averaging these five results. This aimed to eliminate the disadvantages inherent in each method.

Keywords

FMEA,
Multi-Criteria Decision-Making Techniques,
Fuzzy set

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1. INTRODUCTION

Today, businesses are in intense competition. This situation has reduced the chances of companies making mistakes to zero. Companies have to work with zero failures to satisfy their customers. In this case, it is not enough to solve existing failures. The likelihood of failure must be identified and eliminated before it occurs. The most commonly used method in this case is FMEA. Determining the current or potential failures with FMEA, the severity, likelihood, and detection of these failures are calculated by scoring. Efforts are made to reduce the scores of high-risk failures identified through the calculation process. As a result of these studies, the related failure is scored again in terms of severity, likelihood, and detection [1]. In this way, the possibility of detected failures occurring again is reduced. Even if a failure occurs, the potential damage that may arise is also reduced.

FMEA is one of the most frequently used methods for detecting existing or potential failures. However, this method has some disadvantages. In particular, scoring tables used for severity, likelihood, and detection limit the decision-makers who analyze in terms of scoring. Therefore, nowadays, by applying

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FMEA studies with the help of a fuzzy set, score restriction can be avoided. If multi-criteria decision-making techniques are used in these methods, the accuracy of the results will be increased [2]. Each multi-criteria decision-making (MCDM) technique has its strengths and weaknesses, which can result in different ranking outcomes. Conventional fuzzy MCDM methods often address satisfaction or risk factors separately, limiting the reliability of long-term assessments [3]. Therefore, considering the results of multiple methods is expected to improve the accuracy of failure prioritization.

A literature review has shown that studies involving more than two multi-criteria decision-making (MCDM) techniques are rare. Additionally, although FMEA has been applied in various industries, comprehensive studies in the connecting elements sector are lacking. Bolts, nuts, and screws, as essential connecting elements, are fundamental products that ensure structural integrity and safety, particularly in the automotive, aerospace, and construction industries. Even minor defects in these components can lead to financial losses and safety issues.

The heat treatment process, a critical stage in the production of these products, enhances their hardness, strength, and durability, making them of vital importance. However, processes involved in heat treatment can result in defects such as cracks, dimensional inaccuracies, and surface irregularities. Addressing and eliminating potential issues during this stage is crucial, as it reduces error rates in subsequent stages and lowers scrap rates. Therefore, this study conducts an FMEA focusing on the heat treatment of connecting elements. By targeting the most critical and error-prone process in the sector, the study aims to improve the reliability of the final product.

2. CONCEPTUAL FRAMEWORK AND LITERATURE REVIEW

FMEA is a method that aims to evaluate potential failures and prevent them before they occur by questioning what could go wrong and the consequences of those failures, thus ensuring quality from the very beginning [4].

While FMEA measures severity, likelihood, and detectability based on expert knowledge, measuring risk factors remains challenging. The relative changes in the experts' importance rankings can prevent FMEA from providing clear and accurate results. In this study, five different fuzzy multi-criteria decision-making methods weighted with DEMATEL were employed. Previous research that calculated FMEA using these methods was reviewed, as summarized in Table 1. However, no studies were found that utilized all five methods together.

Table 1. Literature Review

Method	Reference	Year	Subject of Article
VIKOR	Safari et al.[5]	2016	The authors identify and evaluate enterprise architecture risks using FMEA and fuzzy VIKOR. The study aims to provide a robust framework for assessing risks associated with enterprise architecture.
	Hajiagha et al. [6]	2016	This article presents a fuzzy belief structure-based VIKOR method to rank the causes of delays in the Tehran metro system using FMEA criteria, focusing on improving project management and efficiency.
	Yang et al.[7]	2021	The study improves FMEA by employing the IVF and fuzzy VIKOR methods, using a case survey of the workpiece box system in CNC gear milling machines to demonstrate enhanced risk evaluation.
MOORA	Arabsheybani et al. [8]	2018	This study proposes an integrated fuzzy MOORA method and FMEA technique for sustainable supplier selection, considering quantity discounts and supplier risks to optimize procurement processes and risk assessment.
	Mete [9]	2019	This research assesses occupational risks in pipeline construction using an FMEA-based AHP-MOORA integrated approach within a Pythagorean fuzzy environment, aiming to improve safety and risk management practices.
	Emovon and Mgbemena [10]	2019	The article enhances the FMEA technique by combining Expectation interval, TAGUCHI, MOORA, and Geometric mean methods, focusing on improving risk analysis and decision-making processes in industrial engineering.
GRA	Liu et al. [11]	2015	The article evaluates risks in FMEA using an extended VIKOR method under fuzzy conditions, aiming to provide a more nuanced assessment of potential failure modes in various applications.
	Shi et al. [12]	2019	This research applies an FMEA method that combines interval 2-tuple linguistic variables and grey relational analysis in preoperative medical service processes, focusing on improving healthcare service quality and safety.
FMEA	Turan et al. [13]	2019	It is a technique aimed at increasing the reliability of the process and eliminating potential errors, ensuring that mistakes are prevented before reaching customers.
TOPSIS	Kuei et al.[14]	2014	This article integrates the TOPSIS and DEMATEL methods to rank failure risks in FMEA. It aims to enhance decision-making by effectively identifying and prioritizing potential failure modes.
	Hu et al. [15]	2019	The article "Improving Risk Evaluation in FMEA With Cloud Model and Hierarchical TOPSIS Method" presents a method for enhancing risk assessment in FMEA by integrating a Cloud model and hierarchical TOPSIS. This approach addresses uncertainties and complexities, providing more accurate and reliable risk evaluations. The authors illustrate the effectiveness of this combined method through examples and results.
	Mangelia et al. [16]	2019	The study improves risk assessment in FMEA using a nonlinear model, revised fuzzy TOPSIS, and Support Vector Machine. It seeks to enhance the accuracy of risk evaluations through advanced analytical techniques.
	Ersadi and Forouzandeh [17]	2019	This research proposes a hybrid approach for managing information security risks in research information systems. It integrates Fuzzy FMEA, AHP, TOPSIS, and Shannon Entropy to establish a comprehensive risk assessment framework.

3. METHODS

In this study, the most commonly used methods among multi-criteria decision-making techniques have been prioritized. Multi-criteria decision-making (MCDM) methods are widely used in the literature to solve decision problems and rank alternatives. In this study, the TOPSIS, MOORA, GRA, and VIKOR methods were selected. The reasons for choosing these methods are their flexibility, ease of use, and ability to consider different optimization aspects. In particular, these methods enable the evaluation of multiple criteria while being sensitive to the preferences and weights assigned by decision-makers. Additionally, their ability to handle uncertainty and incomplete data enhances their applicability. The GRA method is more suitable for dealing with uncertain data, while the VIKOR method aims to achieve optimal solutions by providing compromise solutions. The fuzzy versions of these methods are used to manage uncertainty more effectively. It has been stated that the selected methods utilize statistical analyses; in this context, weighting, normalization, calculation of criterion weights, and ranking techniques are emphasized. Therefore, these methods are preferred not only for their mathematical foundations but also for the practical benefits they offer in real-world applications. [18,19,20,21]

Multi-criteria decision-making techniques are used to solve problems that managers frequently encounter daily. Managers use this method in real-life issues that they are accustomed to solving and in managerial decision-making processes that they have to solve using mathematics and statistics. Thanks to this method, multiple and conflicting objectives are solved most accurately [22].

The methods used in this study are DEMATEL, VIKOR, TOPSIS, MOORA, and GRA relational analysis methods, and detailed information about them is given in the following headings.

3.1. DEMATEL Method

The DEMATEL method was first developed by the Geneva Battelle Memorial Institute between 1972 and 1976 to address complex problems [23].

The DEMATEL method examines the criteria determined for the related problems under two headings: the cause criteria, which have a greater impact on the other criteria, and the result criteria, which are influenced by other important criteria [24].

In the relevant study, the weighting of severity, likelihood, and detectability scores was conducted using the traditional DEMATEL method instead of the fuzzy DEMATEL approach. This weighting was conducted with a single decision-maker within the company. Therefore, the conventional DEMATEL method was chosen over fuzzy DEMATEL for weighting.

It is possible to apply the DEMATEL method in five steps. These steps and the formulas used are as follows:

Step 1: Creating the Direct Relationship Matrix: In this step, experts on the subject examine how the criteria determined for the relevant subject affect each other, and in the case of N number of experts, N nxn matrices are created [25].

$$\boldsymbol{a_{ij} = \frac{1}{N}\sum_{k=1}^{N} x_{ij}^{k}} \quad (1)$$

The situation where the relevant experts examined the relationship between the determined criteria and scored these relationships is shown in Table 2.

Table 2. Dematel Evaluation Chart [26]

Numerical Method	Definition
0	Ineffective
1	Low Effective
2	Moderate Effective
3	Highly Effective
4	Very Highly Effective

Step 2: Normalizing the Direct Relationship Matrix: The direct relationship matrix created with the help of equation (2) and equation (3) shown below is normalized using the smallest values in its rows and columns. The diagonal values of the normalized X matrix are 0 [27].

$$\boldsymbol{X = k.A} \tag{2}$$

$$\boldsymbol{k} = \frac{\boldsymbol{1}}{\boldsymbol{max \sum_{j=1}^{n} a_{ij}}} \qquad \text{i, j} = 1, 2, \ldots\ldots, \text{n} \tag{3}$$

Step 3: Creating the Total Relationship Matrix: After the direct relationship matrix is normalized, the total relationship matrix (T) is created using equation (4). The 'I' in the equation denotes the unit matrix [28].

$$\boldsymbol{T = X(I - X)^{-1}} \tag{4}$$

Step 4: Identifying Influencing and Affected Values: At this stage, the sum of the effect matrices' rows and columns is found using equations (5) and (6). A D vector is used for row sums, and an R vector is used for column sums [29].

$$\boldsymbol{D = [\sum_{i=1}^{n} t_{ij}]_{ixn} = [t_j]_{nx1}} \tag{5}$$

$$\boldsymbol{R = [\sum_{j=1}^{n} t_{ij}]_{ixn} = [t_j]_{1xn}} \tag{6}$$

Step 5: Calculating the Importance Weights of the Criteria: At this stage, as shown in equation (7), the total effects of the D and R vectors and the squared average of the net effects are calculated and the importance weights of the criteria are calculated. [29].

$$\boldsymbol{w_i = [(D_i + R_i)^2 + (D_i - R_i)^2]^{1/2}} \tag{7}$$

3.2. Fuzzy TOPSIS Method

The TOPSIS method is a multi-criteria decision-making method used to find the best alternative that is the farthest from the best negative alternative solution and closest to the best positive alternative solution [30].

Table 3. Linguistic Expression of the Significance Levels of the Criteria [44]

Numerical Method	Fuzzy Number Equivalent
Very Low	1,1,3
Low	1,3,5
Average	3,5,7
High	5,7,9
Very High	7,9,9

Table 3 presents the linguistic expressions and their corresponding values used for the criteria in the fuzzy TOPSIS method.

Note: The scales used in Table 3 have been applied in all multi-criteria decision-making techniques other than DEMATEL.

Step 1: Creating the Unified Decision Matrix: After the scores given by the decision makers are converted into fuzzy numbers, the decision matrices are combined using Equation (8) and Equation (9).

$$x_{ij} = (a_{ij}, b_{ij}, c_{ij}) \tag{8}$$

$$a_{ij} = min_k(a_{ij}^k),\ \ b_{ij} = \frac{1}{K}\sum_{k=1}^{K} b_{ij}^k,\ \ c_{ij} = max_k(c_{ij}^k) \tag{9}$$

Step 2: Creating the Normalized Decision Matrix: Depending on whether the criteria in the combined decision matrix are benefit or cost-based, Equation (10) is applied for benefit criteria, while Equation (11) is used for cost criteria [31].

$$r_{ij} = (\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}) \text{ and } c_j^* = max_i(c_{ij}) \tag{10}$$

$$r_{ij} = (\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}) \text{ and } a_j^- = min_i(a_{ij}) \tag{11}$$

Step 3: Calculation of the Weighted Normalized Decision Matrix: Equation (12) helps find the weights of the criteria to be evaluated and the weighting of the normalized decision matrix [31].

$$v_{ij} = r_{ij} x w_{ij} \tag{12}$$

Step 4: Calculating Fuzzy Positive and Negative Ideal Solutions: To find the closest results to the ideal solution, the ideal positive solution is found using equation (13), and the ideal negative solution is found using equation (14) [32].

$$\text{When } v_j^* = max_i(v_{ij3}),\ A^* = (v_1^*, v_2^*, \ldots v_n^*) \tag{13}$$

$$\text{When } v_j^- = min_i(v_{ij1}),\ A^- = (v_1^-, v_2^-, \ldots v_n^-) \tag{14}$$

Step 5: Calculating Distance to Ideal Solutions: After identifying the ideal solutions, the distances of the alternatives' criteria from the ideal positive solution to the ideal negative solution are calculated using the equation (15) [31].

$$d(x, y) = \sqrt{(\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2])} \tag{15}$$

Step 6: The Distance of Each Alternative to the Ideal Positive and Ideal Negative Solution: Equation (16) and equation (17) are applied to the criteria of each alternative determined in this section [31].

$$d_i^* = \sum_{j=1}^{n} d(v_{ij}, v_j^*) \tag{16}$$

$$d_i^- = \sum_{j=1}^{n} d(v_{ij}, v_j^-) \tag{17}$$

Step 7: Calculating the Closeness Coefficient for Each Alternative: The closeness coefficient for each alternative is calculated using equation (18). The results are ordered from the largest to the smallest, and the best solution is found [33].

$$CC_I = \frac{d_i^-}{d_i^- + d_i^*} \tag{18}$$

3.3. Fuzzy MOORA Method

The fuzzy MOORA method, first introduced by Brauers and Zavadskas in public privatization studies, is a multi-objective optimization approach that provides alternative solutions using proportional analysis in various decision-making problems [34].

The steps of the fuzzy MOORA method can be listed as follows. While the steps are being sequenced, the formation of fuzzy numbers and the creation of the composite decision matrix are the same as fuzzy TOPSIS, so those steps are not explained again. In explaining the subsequent multi-criteria decision-making techniques, this calculation was performed in advance. Therefore, other stages proceeded without reiterating this calculation in the formulas.

Step 1: Creating Decision Matrix with Vector Normalization: In this step, the decision matrix is normalized by applying the operations in Equations (8) and (9). In this step, all three fuzzy numbers are normalized with the help of equations (19), equations (20), and equations (21) so that the normalization process is more accurate and pairwise comparisons can be made better [35].

$$r_{ij}^l = \frac{x_{ij}^l}{\sqrt{(\sum_{i=1}^m [(x_{ij}^l)^2 + (x_{ij}^m)^2 + (x_{ij}^n)^2])}} \tag{19}$$

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

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

Step 2: Creating the Weighted Normalized Decision Matrix: In this step, weighted normalized decision matrices are created by using Equation (22), Equation (23), and Equation (24) [36].

$$v_{ij}^l = w_j r_{ij}^l \tag{22}$$

$$v_{ij}^m = w_j r_{ij}^m \tag{23}$$

$$v_{ij}^n = w_j r_{ij}^n \tag{24}$$

Step 3: Calculating Alternatives in Terms of Benefit Criteria: Equations (25), (26), and (27) for the utility criterion; Equations (28), (29), and (30) are used for the cost criterion [35].

$$S_i^{+l} = \sum_{j=1}^n v_{ij}^l | j \in J^{max} \tag{25}$$

$$S_i^{+m} = \sum_{j=1}^n v_{ij}^m | j \in J^{max} \tag{26}$$

$$S_i^{+n} = \sum_{j=1}^{n} v_{ij}^{n} | j \in J^{max} \tag{27}$$

$$S_i^{-l} = \sum_{j=1}^{n} v_{ij}^{l} | j \in J^{min} \tag{28}$$

$$S_i^{-m} = \sum_{j=1}^{n} v_{ij}^{m} | j \in J^{min} \tag{29}$$

$$S_i^{-n} = \sum_{j=1}^{n} v_{ij}^{n} | j \in J^{min} \tag{30}$$

Step 4: Establishing the Performance Value of Each Alternative: Equation (31) helps create the performance value of each alternative as follows [35].

$$S_i(s_i^{+}, s_i^{-}) = \sqrt{(\frac{1}{3}[(s_i^{+l} - s_i^{-l})^2 + (s_i^{+m} - s_i^{-m})^2 + (s_i^{+n} - s_i^{-n})^2])} \tag{31}$$

Step 5: Ranking of Alternatives: The performance index values are analyzed, and the alternatives are ranked accordingly, with the highest-scoring alternative being preferred [36].

3.4. Fuzzy Gray Relational Analysis Method

While the term 'Gray' implies weakness, incompleteness, or uncertainty, Gray Relational Analysis is a method of ranking alternatives by comparing all available criteria in problems that lack sufficient data in multivariate situations or cannot be solved due to uncertainty. [37]. Since the Gray relational analysis method is a solution applied to decision problems in complex relationships, it can be used together with other multi-criteria decision-making techniques or can be used alone [37].

The stages of Gray relational analysis are as follows. Since the conversion of verbal values to fuzzy values is calculated as in fuzzy TOPSIS and fuzzy MOORA, that step is skipped and explanations of other stages are given.

Step 1: Creating the Normalized Decision Matrix: In this step, Equations (32) and (33) below are used, taking into account benefit or cost considerations [38]. The key aspect is whether our decision criteria result in costs or benefits.

$$r_{ij} = (\frac{l_{ij}}{u_j^{+}}, \frac{m_{ij}}{u_j^{+}}, \frac{u_{ij}}{u_j^{+}}), \quad \text{i=1,….m,} \quad \text{j=1,….n if } r_j^{+} = mak_i r_{ij} \tag{32}$$

$$r_{ij} = (\frac{l_j^{-}}{u_{ij}}, \frac{l_j^{-}}{m_{ij}}, \frac{l_j^{-}}{l_{ij}}), \quad \text{i=1,….m,} \quad \text{j=1,….n if } l_j^{-} = min_i l_{ij} \tag{33}$$

Step 2: Determination of the Reference Series: With the help of equation (34) if the objective function is maximizing, and equation (35) if the objective function is minimization, the alternatives that should be chosen to achieve the desired situation in the decision matrix are determined one by one, and a reference series is created [38].

$$\boldsymbol{R_0} = [\boldsymbol{r_{01}}, \boldsymbol{r_{02}}, \ldots . \boldsymbol{r_{0n}} = \boldsymbol{max}(\boldsymbol{r_{ij}})] \quad \text{j=1,2,....n} \tag{34}$$

$$\boldsymbol{R_0} = [\boldsymbol{r_{01}}, \boldsymbol{r_{02}}, \ldots . \boldsymbol{r_{0n}} = \boldsymbol{min}(\boldsymbol{r_{ij}})] \quad \text{j=1,2,....n} \tag{35}$$

Step 3: Creating the Distance Matrix: The distance matrix is calculated using Equation (36), and the distances of the values in the normalized decision matrix to the reference series are determined using the matrix created by this formula. [38].

$$\boldsymbol{d(A,B)} = \sqrt{(\tfrac{1}{3}[(\boldsymbol{l_1} - \boldsymbol{l_2})^2 + (\boldsymbol{m_1} - \boldsymbol{m_2})^2 + (\boldsymbol{u_1} - \boldsymbol{u_2})^2])} \tag{36}$$

Step 4: Creating the Gray Relational Coefficient Matrix: The formula used to construct the Gray relational coefficient matrix is shown in Equation (37).

$$\boldsymbol{y_{0i}(j)} = \frac{\boldsymbol{\delta_{min}} + \zeta\boldsymbol{\delta_{max}}}{\boldsymbol{\delta_{0i}(j)} + \zeta\boldsymbol{\delta_{max}}}, \qquad \boldsymbol{\delta_{max}} = \boldsymbol{max_i max_j \delta_{0i}(j)}, \qquad \boldsymbol{\delta_{min}} = \boldsymbol{min_i min_j \delta_{0i}(j)} \tag{37}$$

The $\boldsymbol{\zeta}$ specified in Equation (37) is a determinant value. It takes a value between 0 and 1. In the literature, this value is usually taken as 0.5. [39]. Even if this coefficient takes a value other than 0.5, the final ranking of the alternatives will remain unchanged. If the value is greater than 0.5, the alternatives move closer to the desired value, whereas if it is less than 0.5, they move away from the desired values [38].

3.5. Fuzzy VIKOR Method

The VIKOR method, a multi-criteria decision-making technique, was developed by Opricovic to assist decision-makers when they are unable to determine or specify their preferences [40]. The fuzzy VIKOR method can be defined as follows: It is a method used to solve discrete fuzzy multi-criteria decision-making techniques that are too conflicting to be compared with each other.

The following steps should be followed while applying this method. Since the conversion of verbal values to fuzzy values is calculated as in fuzzy TOPSIS, fuzzy Gray relational analysis, and fuzzy MOORA, that step is skipped, and explanations of other stages are given.

Step 1: Determining the Best and the Worst Fuzzy Value: In this step, each column is analyzed individually, and the maximum and minimum values are calculated using Equations (38) and (39) [41].

$$\boldsymbol{f_j^*} = \boldsymbol{max_i x_{ij}} \tag{38}$$

$$\boldsymbol{f_j^-} = \boldsymbol{min_i x_{ij}} \tag{39}$$

Step 2: Determination of $\boldsymbol{S_j}$ and $\boldsymbol{R_j}$ Values: $\boldsymbol{S_j}$ and $\boldsymbol{R_j}$ values are calculated using Equations (40) and (41) below. In these equations, $\boldsymbol{w_i}$ represents the criteria weights. $\boldsymbol{S_j}$ denotes the sum of the distances between the "ith" alternative and the best fuzzy value across all criteria, while $\boldsymbol{R_j}$; represents the distance of the "ith" alternative from the fuzzy worst value according to the "jth" criterion [41].

$$\boldsymbol{S_j} = \sum_{\boldsymbol{j=1}} [\boldsymbol{w_i}(\boldsymbol{f_i^*} - \boldsymbol{x_{ij}})/(\boldsymbol{f_i^*} - \boldsymbol{f_i^-})] \tag{40}$$

$$R_j = max[w_i(f_i^* - x_{ij})/(f_i^* - f_i^-)] \quad (41)$$

Step 3: Determination of Q_i Values with the Help of $S_j^-, S_j^*, R_j^-, R_j^*$: With the help of equation (42) and equation (43) shown below S_j^*, which is the rule of maximum majority, and R_j^*, which expresses the minimum individual regret of those with different opinions. After these calculations, Q_i is found with the help of equation (44) [42].

$$S_j^* = min_j S_j, S_j^- = max S_j \quad (42)$$

$$R_j^* = min_j R_j, R_j^- = max R_j \quad (43)$$

$$Q_j = v(S_j - S^*)/(S^- - S^*) + (1 - v)(R_j - R^*)/(R^- - R^*) \quad (44)$$

Step 4: Clarifying Q_i Values: At this stage, using the BNP (Best Nonfuzzy Performance Value) method, u_i blurring is provided, with m_i showing the upper value of the fuzzy number, l_i the middle value, and Q_i the lower value, and Q_i is used in the ranking of the alternatives [43].

$$BNP_i = [(u_i - l_i) + (m_i - l_i)]/3 + l_i \quad (45)$$

Step 5: Checking If the Best Alternatives Are the Reconciliatory Solution: The alternative conciliatory solution is identified if both conditions are met, with the stages outlined below.

Condition 1: Acceptable Advantage

$$Q(A^{--}) - Q(A^-) \geq DQ \quad (46)$$

$$DQ = \frac{1}{(m-1)} \quad (47)$$

With the help of this equality, the number of alternatives represents the first alternative and the second best alternative [44].

Condition 2: Acceptable Stability

The best alternative should rank as the best in at least one of the S or R-value orderings. On the other hand, if the 1st condition cannot be met at the same time, we can say that $Q(A^m) - Q(A^-) < DQ$ are solutions similar to (A^m) and (A^-) alternatives [45].

Step 6: Choosing the Best Alternative: In this step, the alternative with the smallest Q value is selected as the best alternative [45].

4. CASE STUDY

This study presents a hybrid model proposal for the evaluation process of FMEA. The proposed model was applied in the heat treatment process of a fastener factory.

A review of the literature in the relevant sector reveals no prior studies of this nature. Additionally, given that the fasteners sector directly influences many other industries, addressing failures in this sector is expected to have a direct impact on those industries as well.

The failures that may occur in the department were determined by brainstorming with 1 Chemist who is the process owner, 1 Metallurgical and Materials Engineer, 1 Industrial Engineer who manages the processes before the heat treatment process, and 1 Chemist who is the department manager responsible for coating the material after the heat treatment process. All relevant failure identifiers were determined by personnel directly involved in the heat treatment process. The identified failures were then categorized into two groups: those affecting the process and those affecting the product.

The brainstorming method has identified all the failures. A total of 16 failures affecting the process have been identified. Additionally, 18 failures affecting the product have been identified.

Subsequently, analyses were conducted using DEMATEL-weighted fuzzy TOPSIS, fuzzy MOORA, fuzzy Gray Relational Analysis, fuzzy VIKOR, and classical FMEA methods. As part of the application, process-related failures were identified, as presented in Tables 4 and 5.

Table 4. Failures Affecting the Product in the Heat Treatment Section

Identified Product Failures
The operator throws the wrong product into the oven due to a problem logging into the ERP program.
Poor circulation in the oven
Deterioration of the remaining material in the furnace caused by a power outage.
Product deterioration due to natural gas supply interruption
Washing bath temperatures are not high enough
Inappropriate products produced
The uneven hardness of the bottom product due to excessive product loading in the oven
Oven indicators not working correctly
The curvature of the tape roll caused by a power outage
Heat loss caused by improper insulation
Malfunction of the methanol sprinkler system
Oven belt malfunction
Burning of oil in the furnace mouth caused by a power outage
Incorrect hardness measurement
Failure to form the right atmosphere due to lack of proper insulation
Clogged bath units due to sawdust

Table 5. Failures Affecting the Process in the Heat Treatment Section

Identified Process Failures
Disruption of production due to problems in entering the ERP program
COVID-19 and other work interruptions due to circumstances or conditions.
Failure to process new products originating from reprocessing
Lack of necessary tools or parts during troubleshooting
Failure of components due to power outage
No products from production
Working with missing personnel
No serial products from production
Clogging of heat treatment lines
Inappropriate products from production
Absence of methanol or heat treatment oil required for the operation of the furnace
Unplanned maintenance
Product jamming in the furnace due to excessive product loading in the heat treatment furnace
Oven belt malfunction
Clogging of nozzles at the end of the line
Late product loading due to forklift malfunction or lack of availability
Boilers not being fully loaded before coming from production
Clogged bath units due to sawdust

Since the evaluation of FMEA is subjective, it was decided to use multi-criteria decision-making techniques. The fuzzy set method and multi-criteria decision-making techniques were employed to improve the clarity of verbal expressions. The goal was to minimize the potential shortcomings inherent in multi-criteria decision-making techniques. Therefore, a new hybrid model was developed by integrating four different multi-criteria decision-making techniques with the classical FMEA method.
After the grouping process was made, the severity, likelihood, and detection of each failure were evaluated verbally by the responsible persons determined on a 5-point scale as very high, high, medium, low, and very low. The fuzzy multi-criteria decision-making techniques, determined based on the responses received, were applied sequentially, and a ranking was generated for each.

4.1. Criteria Weighting with DEMATEL Method

Before moving on to fuzzy multi-criteria decision-making methods, severity, likelihood, and detection, which are the criteria determined for FMEA, were weighted with the DEMATEL method.

The weighting process was carried out by the company's quality management officer, and its steps are outlined below.

In this study, Equation (1) was not applied since there is only one decision-maker. Table 6 was created using Table 3 as a reference for severity, likelihood, and detectability.

Table 6. Creation of the Direct Relationship Matrix

Criteria	Severity	Likelihood	Detection
Severity	0	0	3
Likelihood	0	0	2
Detection	0	4	0

In the subsequent steps, the following tables were created sequentially using Equations (2), (3), (4), (5), (6), and (7).

Table 7. Normalized Direct Relationship Matrix

Criteria	Severity	Likelihood	Detection
Severity	0,000	0,000	0,600
Likelihood	0,000	0,000	0,400
Detection	0,000	0,800	0,000

In this step, the rows and columns are added together and the k value is calculated using equation (3). As a result of the operation, the k value is calculated as 0.2. As a result of the calculation, the direct relationship matrix created using the formula specified in equation (2) is normalized. The normalized direct relationship matrix resulting from the calculation is shown in Table 7.

Table 8. Total Relationship Matrix

Criteria	Severity	Likelihood	Detection
Severity	0,000	0,000	0,529
Likelihood	0,000	0,000	0,235
Detection	0,000	0,941	0,000

In this step, the total relationship matrix was created using the identity matrix and equation (4) as shown in Table 8.

Table 9. Influencing and Affected Values

Criteria	D Vector	R Vector
Severity	0,529	0,000
Likelihood	0,235	0,941
Detection	0,941	0,765

In this step, the row and column sums are taken according to equation (5) and equation (6), and the D vector and R vector are created as in Table 9.

Table 10. Calculation of Criterion Importance Weights

Criteria	Criterion Significance Weight
Severity	0,195
Likelihood	0,358
Detection	0,447

In this step, the importance weights of the criteria were calculated based on the net effects of the D and R vectors with the help of equation (7). As a result of the calculation, the importance weights of the criteria were calculated as in Table 10.

The dematel-weighted failures determined with the help of the above-mentioned formulas were solved by each method one by one, and the combined decision matrices were created as shown in Table 11 and Table 12.

Table 11. Unified Decision Matrix for Processes

Failures Affecting the Process	Severity			Likelihood			Detection		
Disruption of production due to problems in entering the ERP program	1	2,5	7	1	4,5	9	1	5	9
COVID-19 and other work interruptions due to circumstances or conditions.	3	7	9	1	5	9	3	5	7
Working with missing personnel	1	6,5	9	1	6	9	1	2,5	5
No serial products from production	1	5,5	9	3	5,5	9	3	6	9
Product jamming in the furnace due to excessive product loading in the heat treatment furnace	3	6,5	9	1	4	7	1	6,5	9
Oven belt malfunction	5	8	9	1	4	7	1	4,5	9
Failure of components due to power outage	5	8	9	1	3,5	9	1	3	9
Absence of methanol or heat treatment oil required for the operation of the furnace	7	9	9	1	1,5	5	1	6	9
No products from production	1	6	9	1	2,5	5	1	5,5	9
Unplanned maintenance	5	7,5	9	1	3,5	9	1	2,5	7
Failure to process new products originating from reprocessing	3	5,5	9	1	2	5	1	4,5	9
Clogging of heat treatment lines	1	6	9	1	4,5	9	1	4	7
Clogging of nozzles at the end of the line	1	5,5	9	1	4,5	9	3	6,5	9
Boilers not being fully loaded before coming from production	1	4	7	3	7,5	9	1	3,5	9
Clogged bath units due to sawdust	3	6	9	1	5,5	9	1	5	9
Lack of necessary tools or parts during troubleshooting	5	7,5	9	1	4	9	1	3	7
Inappropriate products from production	1	2,5	7	1	3,5	9	1	4,5	9
Late product loading due to forklift malfunction or lack of availability	5	8	9	1	6	9	1	3,5	7

Table 12. Unified Decision Matrix for Products

Failures Affecting the Product	Severity			Likelihood			Detection		
The operator throws the wrong product into the oven due to a problem logging into the ERP program	1	2,5	7	1	4,5	9	1	5	9
The uneven hardness of the bottom product due to excessive product loading in the oven	3	7	9	1	5	9	3	5	7
Oven belt malfunction	1	6,5	9	1	6	9	1	2,5	5
Poor circulation in the oven	1	5,5	9	3	5,5	9	3	6	9
Oven indicators not working correctly	3	6,5	9	1	4	7	1	6,5	9
Burning of oil in the furnace mouth caused by a power outage	5	8	9	1	4	7	1	4,5	9
Deterioration of the remaining material in the furnace caused by a power outage	5	8	9	1	3,5	9	1	3	9
The curvature of the tape roll caused by a power outage	7	9	9	1	1,5	5	1	6	9
Incorrect hardness measurement	1	6	9	1	2,5	5	1	5,5	9
Product deterioration due to natural gas supply interruption	5	7,5	9	1	3,5	9	1	2,5	7
Heat loss caused by improper insulation	3	5,5	9	1	2	5	1	4,5	9
Failure to form the right atmosphere due to lack of proper insulation	1	6	9	1	4,5	9	1	4	7
Washing bath temperatures are not high enough	1	5,5	9	1	4,5	9	3	6,5	9
Malfunction of the methanol sprinkler system	1	4	7	3	7,5	9	1	3,5	9
Clogged bath units due to sawdust	3	6	9	1	5,5	9	1	5	9
Inappropriate products produced	5	7,5	9	1	4	9	1	3	7

4.2. FMEA Application with Fuzzy TOPSIS, MOORA, GRA and VIKOR Methods

FMEA calculations were made with fuzzy TOPSIS, MOORA, Gray relational analysis, and VIKOR methods with the help of the above-mentioned formulas. In addition, the classical FMEA method was also applied. The risk rankings of the 5 methods are as in the tables below.

A new ranking was created from the ranking of 5 methods with a new method by scoring over the relevant rankings.

Rankings have been created for five different results, and each method's rankings have been weighted internally. For instance, in the list prepared for failures affecting the process, the failure ranked highest in each method is assigned the highest weight, starting from 18 and decreasing for subsequent rankings. (The intention here is to assign greater importance to the failure ranked first. The weighting is based on the total number of failures identified in the relevant area, which is 18; thus, the highest-ranked failure is given a weight of 18.) This weighting process has been applied to all methods, and the total weight for each failure has been calculated. Based on these totals, a final ranking of failures has been established, ordered from the highest weight to the lowest. As a result of this analysis, the final lists are presented in Table 13 and Table 14.

Table 13. Final FMEA Ranking of Failures Affecting the Process

Failures Affecting the Process	TOPSIS	MOORA	GRA	VIKOR	FMEA	Total
No serial products from production	2	15	18	18	12	65
Working with missing personnel	17	16	11	3	16	63
COVID-19 and other work interruptions due to circumstances or conditions.	3	17	16	16	7	59
Clogged bath units due to sawdust	12	4	13	8	18	55
Unplanned maintenance	14	9	7	9	14	53
Lack of necessary tools or parts during troubleshooting	15	3	9	10	15	52
Absence of methanol or heat treatment oil required for the operation of the furnace	8	11	12	15	6	52
Boilers not being fully loaded before coming from production	16	5	15	14	1	51
Failure of components due to power outage	13	12	8	12	5	50
Clogging of nozzles at the end of the line	1	6	17	17	8	49
Late product loading due to forklift malfunction or lack of availability	18	1	14	13	2	48
Oven belt malfunction	11	13	10	11	3	48
Disruption of production due to problems in entering the ERP program	7	18	4	2	10	41
Clogging of heat treatment lines	10	7	6	5	11	39
Product jamming in the furnace due to excessive product loading in the heat treatment furnace	9	14	5	7	4	39
No products from production	4	10	2	4	13	33
Inappropriate products from production	6	2	3	1	17	29
Failure to process new products originating from reprocessing	5	8	1	6	9	29

When Table 13 is examined, while the errors affecting the process are listed, coefficients starting from 18 to 1 are assigned to the values at the top of the ranking. The coefficients for the relevant error in the five calculation methods are collected and ranked from largest to smallest. In this case, the error that affects the process the most is the failure to receive mass-production products.

Table 14. Final FMEA Ranking of Failures Affecting the Product

Failures Affecting the Product	TOPSIS	MOORA	GRA	VIKOR	FMEA	Total
Oven belt malfunction	16	14	14	15	7	66
Deterioration of the remaining material in the furnace caused by a power outage	12	10	12	16	10	60
Clogged bath units due to sawdust	11	2	15	12	16	56
Oven indicators not working correctly	8	12	9	13	12	54
Product deterioration due to natural gas supply interruption	13	7	10	10	9	49
Malfunction of the methanol sprinkler system	15	3	11	11	8	48
Incorrect hardness measurement	4	8	13	14	6	45
Failure to form the right atmosphere due to lack of proper insulation	9	5	7	8	11	40
The curvature of the tape roll caused by a power outage	7	9	16	6	1	39
The operator throws the wrong product into the oven due to a problem logging into the ERP program	6	16	6	3	5	36
Inappropriate products produced	14	1	2	2	14	33
Heat loss caused by improper insulation	5	6	3	4	15	33
The uneven hardness of the bottom product due to excessive product loading in the oven	3	15	4	7	4	33
Poor circulation in the oven	2	13	5	9	3	32
Washing bath temperatures are not high enough	1	4	8	5	13	31
Burning of oil in the furnace mouth caused by a power outage	10	11	1	1	2	25

In Table 14, the same weighting method was used to rank the products by giving coefficients between 1 and 16. In this ranking, it is seen that the most important fault affecting the product is the malfunction of the oven band.

5. CONCLUSIONS

The most basic rule that businesses must comply with to satisfy their customers is to offer a faultless product or service to the customer. To address this issue, businesses employ various methods to detect failures. Thanks to these measures, failures occurring during production are identified and halted before advancing to the next stages, preventing them from reaching the customer. However, this means both extra work and loss of money for businesses. In addition, potential failures can be overlooked because classical quality control methods see failures after they occur and try to take precautions. For such cases, potentials are measured with FMEA before failures occur, and if necessary, precautions are taken and the likelihood of failure occurring is prevented.

Although the FMEA method ranks failures based on their importance, this ranking may not accurately reflect reality due to the rigidity of the assigned scores. To prevent this, it has been predicted that FMEA ranking and comparison with more than one fuzzy multi-criteria decision-making technique weighted with DEMATEL will yield more accurate results. Thus, the disadvantages of all the methods used will be mitigated to some extent.

In this context, for the heat treatment department of a factory operating in the fastener industry, the failures affecting the products and processes are listed separately by using fuzzy TOPSIS, fuzzy MOORA, fuzzy GRA, fuzzy VIKOR methods, which are fuzzy multi-criteria decision-making techniques. In addition, the classical FMEA method was also applied. The results found were grouped within themselves and a single ranking was created from five separate rankings.

As a result of the literature review on the subject, it has been seen that there are studies in which multiple criteria decision-making techniques are used. However, two methods were generally used in these studies. No study was found in which five different methods were used simultaneously. Additionally, unlike previous studies in the literature, our study conducted an FMEA specifically for product defects. When other studies in the literature are evaluated as the applied sector, no similar study has been found in the fastener sector. For this reason, the study has originality.

The reason for using five different methods is; that the results of each method are different. Therefore, it is important to achieve the most accurate result by minimizing failures in multi-criteria decision-making techniques and classical FMEA.

As a result of the analysis, it was determined that the most important failure affecting the process was “No serial product from production”. For each product type in the heat treatment section, the process needs to be different. For this reason, when different product groups are to be fed into the oven one after the other, the heat treatment band is filled at a distance for two different product groups. This prevents the belt from working efficiently. While planning to eliminate the failure, it was suggested to create a system that would ensure that similar products come one after the other to avoid making constant changes in the heat treatment process and to be able to use the heat treatment band without any gaps.
When the failures affecting the product are examined, it is seen that "Oven belt malfunction" comes first. Failure of the heat treatment furnace band for any reason causes the product to become unusable, especially if there is a product in the furnace. In future studies, the number of currently used multi-criteria decision-making techniques can be increased beyond four, or different multi-criteria decision-making techniques can be employed to analyze how the results might change. In this study, failure mode and effects analysis (FMEA) was applied in the fastener industry using fuzzy multi-criteria decision-making techniques, resulting in an outcome believed to be more accurate. The reason for using multiple techniques in the study is to minimize the margin of error inherent in each method. In future studies, the number of these techniques could be increased to achieve even more accurate results.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

CRediT AUTHOR STATEMENT

Ezgi Günaydın: Formal analysis, Writing – original draft, Investigation, Visualization, Conceptualization**, Mustafa Deste:** Supervision, Visualization, Conceptualization.

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