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Integration of the Failure Mode and Effect Analysis Method with the Fuzzy Analytic Hierarchy Process to Assess Risks and Determine the Priority of Failure Mode: An Applied Research

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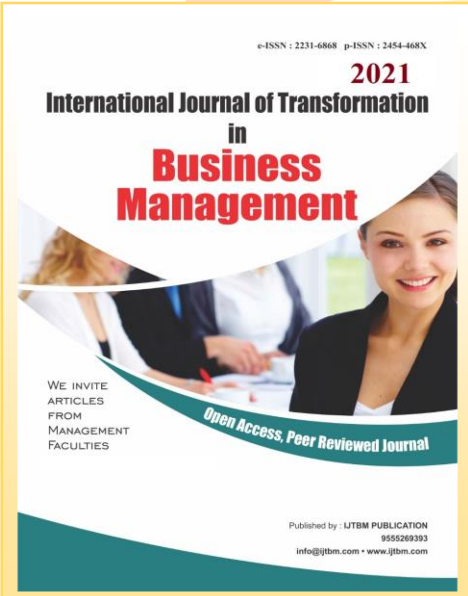

ABSTRACT

In this research, the failure modes and effect analysis (FMEA) and the fuzzy analytic hierarchy process (FAHP) were used in order to help identify and evaluate the risks of known and / or potential failure modes in the boiler in the General Company for Textile and Leather Industries in order to eliminate or reduce their impact. The traditional FMEA method determines the risk priority number (RPN) by multiplying the three risk factors (severity, occurrence, and detection). However, this method has been criticized a lot because it contains many defects or limitations. For example, it does not take into account the relative importance of the three risk factors. The (FAHP) technique was used to determine the relative importance of risk factors as well as to overcome the uncertainty problem. The proposed integration model helps increase accuracy in prioritizing the risk of failure modes by eliminating the disadvantages of the conventional method.

Keywords: FMEA; FAHP, RPN, S, O, D, Risk Assessment

INTRODUCTION

It is very common for failure modes and problems to occur in industries due to the complex nature of industrial systems and processes. These faults result in risks that range from low to high risk. This undesirable matter has increased the importance of risk assessment techniques used in all industries.

There are several techniques that have been developed to conduct risk assessment in order to eliminate or reduce their impact. The Failure Modes and Effect analysis (FMEA) method is one of the most widely used risk assessment tools and one of the modern techniques that have been applied in particular with complex systems to facilitate the process of identifying failure modes in systems and processes and analyzing their causes and effects. FMEA was formally introduced in (1949) by the US Armed Forces (Carlson, 2012). The International Space Agency (NASA) defined it as a scheduled method that works to achieve three main goals, which are identifying possible failure modes, what are their causes and effects, and identifying possible measures to eliminate them or reduce their impact (Ahmed et al, 2014). FMEA provides reliability and safety to system and process and helps to identify failures in processes and systems. The traditional FMEA method relies on the Risk Priority Number (RPN) which is obtained by multiplying the three risk factors (severity, occurrence, detection). However, despite the widespread use of the traditional (FMEA) method, it suffers from some important defects, and the traditional (RPN) method has been criticized for having many limitations (Okoro et al, 2016: 3) (Chanamool and

Naenna, 2016) (Chang, 2016); (Kutlu and Ekmekçioğlu, 2012) (Wang et al., 2009), Many authors have suggested several ways to address the shortcomings of the conventional method in order to accurately assess and rank the failure modes. The integration of (FMEA) with Fuzzy Analysis Hierarchy process (FAHP) is to assess and rank the risk of failure modes. FAHP is one of the MCDM multi-criteria decision-making methods with fuzzy logic. It was used to get rid of the defects of the traditional method and obtain more objective results, as it enables experts to express their linguistic preferences and convert these preferences into a quantitative form for comparison, as it determines the weights of risk criteria and failure modes, In addition to addressing the problem of uncertainty when making decisions.

FAILURE MODE AND EFFECT ANALYSIS

Failure Mode and Effect Analysis (FMEA) is an analytical methodology to systematically identify potential failure modes and assess the associated risks. They are designed to identify known and potential failure modes, their causes and effects on the system or end user, as well as to assess the risks associated with specific failure modes and ranking them in order to proactively and implement corrective actions for the most serious problems in order to enhance the reliability and safety of products, processes, designs or services (Renu et al, 2016) (Liu, 2016). (Ben-Daya et al, 2009) defines it as an engineering method used to identify and define known and / or potential failure modes then eliminate them in the system, design, process and / or service before they reach to the customer.

It is one of the modern and widely spread methods of assessing the risks associated with failure modes in complex systems by using the Risk Priority Number (RPN) and analyzing its causes and effects (AL-Khafaji et al, 2005). (Kudlac et al, 2017) indicates that it is one of the basic analysis methods that are used in the quality management and mainly in the safety and reliability management. Therefore, the FMEA method focuses on preventing defects, enhancing safety and increasing customer satisfaction as defined (McDermott et al, 2009: 1). The risk of failure modes is prioritized using the Risk Priority Number (RPN), which is a mathematical product of three parameters, whose value ranges between (1-1000), used to rank and evaluate the risks of potential failure modes. It is a degree calculated from the following parameters that represent risk factors, namely Severity (S), Occurrence (O), Detection (D), by multiplying them as in the following equation:

RPN = S x O x D.......................... (1)

Severity (S) indicates the severity of the impact resulting from the occurrence of the failure mode if it is not detected or corrected. The Occurrence factor (O) represents the probability that the failure mode will occur for a specific cause, and that means its recurrence. Detection (D) reflects the difficulty in detecting or the inability to detect the failure or the cause of the failure. The scale used to determine the values of S, O, and D, namely 1 to 10 with a different description, can be seen in the following table.

Table (1): The (FMEA) scale of the Severity factor

Rating	Severity	description
10	Hazardous without warning	Very High severity ranking when a potential failure mode effects safety and/or involves noncompliance with government regulations without warning.
9	Hazardous with warning	Very High severity ranking when a potential failure mode affects safety and/or involves noncompliance with government regulations with warning.
8	Very high	The system inoperable, with loss of primary function
7	High	The system operable, but at reduced level of performance.
6	Moderate	The system operable, but comfort/convenience item(s) inoperable. Customer experiences discomfort.
5	Low	The system operable, but comfort/convenience item(s) operable at reduced level of performance. Customer experiences some Dissatisfaction.
4	Very low	Cosmetic defect in finish, fit and finish/squeak or rattle item that does not conform to specifications. Defect noticed by most customers.
3	Minor	Cosmetic defect in finish, fit and finish/squeak or rattle item that does not conform to specifications. Defect noticed by average customer.
2	Very minor	Cosmetic defect in finish, fit and finish/squeak or rattle item that does not conform to specifications. Defect noticed by discriminating customers.
1	None	No effect.

Table (2): The (FMEA) scale of the Detection factor

Rating	Detection	Description
10	Absolutely impossible	Design control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode; or there is no design control
9	Very remote	Very remote chance the design control will detect a potential cause/mechanism and subsequent failure mode
8	Remote	Remote chance the design control will detect a potential cause/mechanism and subsequent failure mode
7	Very Low	Very Low chance the design control will detect a potential cause/mechanism and subsequent failure mode
6	Low	Low chance the design control will detect a potential cause/mechanism and subsequent failure mode
5	Moderate	Moderate chance the design control will detect a potential cause/mechanism and subsequent failure mode

4	Moderately high	Moderately high chance the design control will detect a potential cause/mechanism and subsequent failure mode
3	High	High chance the design control will detect a potential cause/mechanism and subsequent failure mode
2	Very High	Very High chance the design control will detect a potential cause/mechanism and subsequent failure mode
1	Almost certain	Design control will almost certainly detect a potential cause/mechanism and subsequent failure mode

Table (3): The FMEA scale of the Occurrence factor

Rating	Occurrence	Description
10 9	Very High	Often fails
8 7	High	Repeated failure
6 5 4	Medium	Failure is rare
3 2	Low	Very small failure
1	There is no	There is almost no damage

However, despite the widespread use of the traditional (FMEA) method, it suffers from some drawback. (Liu, 2016: 10) summarizes it as follows:

1. The relative importance is not taken into consideration between (S-O-D) values as it is considered with the same weight, and it may not be realistic.
2. Multiplying different values from (S-O-D) may result the same value from (RPN) and their hidden risk may be different.
3. The three risk factors are difficult for (FMEA) team determine accurately.
4. The formula for calculating (RPN) is disputed and lacks a scientific basis, so there is no logical reason to multiplying (S-O-D) to produce RPN.
5. (RPN) takes into account only three safety risk factors and neglects other important risk factors such as economic aspects (e.g. time and cost).

6. The mathematical formula for computing (RPN) is highly sensitive to differences in risk factor assessments.
7. The (RPN) method measures from the point of view of risk while ignoring the importance of corrective actions.

These drawbacks are overcome by (MCDM) methods, and it is often difficult for experts to accurately assess failure modes according to risk criteria, as they prefer to use linguistic variable to present their opinions. The fuzzy logic proposed by (Zadeh, 1965) is applicable when dealing with linguistic terms because it is able to deal with uncertainty. (Bowles et al. 1995) used fuzzy logic for the first time with (FMEA). When fuzzy logic is combined with (MCDM) methods, it is able to provide more applicable decisions.

Objectives of the FMEA

There are many goals for this method that can be summarized in the following points (Carlson, 2012, 22) (Ambekar et al, 2013):

1) To identify potential failures before they occur and reduce their risks, either by proposing design changes or proposing operational procedures and determining their causes and effects.
2) Reducing product performance or process performance decline.
3) Improving process control plans (in the case of an operation).
4) Improving testing and verification plans (in case of system or design).
5) Evaluate the effects of each type of failure on the system.
6) Determining the necessary measures to eliminate or reduce the risks associated with each failure mode.
7) Providing information to operators and supervisors to understand the capabilities and limitations of the system to achieve the best performance.

FUZZY ANALYTIC HIERARCHY PROCESS (FAHP)

The AHP method proposed by Saaty is considered a model for decision-making that helps us in making complex decisions, as it consists of three parts, defining and organizing decision goals, criteria and alternatives in a hierarchy, Pairwise Comparisons, using the solution algorithm to obtain the relative importance of each criterion or Alternative (Saaty, 1988). (AHP) uses the advantages of Fuzzy Set Theory that (Zadeh) introduced in the (1960s), which can include imprecise variables. In the eighties, some scientists began to combine the fuzzy concept with the traditional (AHP) to form the (Fuzzy AHP) (Chan and Wang, 2013,71), and since then the (FAHP) has been applied in many different applications such as (Weck et al, 1997) (Arshinder et al, 2007) (Huang et al, 2008) (Wang et al, 2012). (Buckley, 1985) began using (Trapezoidal Fuzzy Number) to express the decision-maker's assessment of alternatives with respect to each criterion while (Laarhoven and Pedrcyz, 1983) used Triangular Fuzzy Number (TFN). (Chang,1996) introduced a new approach for handling FAHP, with the use of triangular fuzzy numbers for pair-wise comparison scale of FAHP, and the use of the extent analysis method for the synthetic extent values of the pair-wise comparisons (Naghadehi et al, 2009,8219).

Fuzzy set theory has been widely used with AHP because fuzzy set theory enables decision makers to render interval judgments and consider uncertainty or fuzziness (Emrouznejad and Ho, 2017). (FAHP) reflects human way of thinking when dealing with approximate and uncertain information in order to obtain decisions. It also maintains basic (AHP) characteristics, as it facilitates dealing with quantitative and qualitative data, pair wise comparisons and minimizing inconsistencies. (FAHP) is an extension of the traditional AHP, but the latter uses conventional numbers (Crisp), and since ambiguity is a basic feature of decision-making problems, the (fuzzy AHP) was developed to deal with this problem.

The steps to conduct (FAHP)

(FAHP) steps are implemented as follows (Ayhan, 2013, 14):

a) The decision maker compares the criteria or alternatives using the linguistic terms shown in Table (4):

Table (4): Triangular fuzzy numbers of linguistic variables.

Linguistic Variable	Triangular Fuzzy Numbers	Reciprocal Triangular Fuzzy Numbers
Equally strong	(1,1,1)	(1,1,1)
Moderately strong	(2,3,4)	(1/4,1/3,1/2)
Strong	(4,5,6)	(1/6,1/5,1/4)
Very strong	(6,7,8)	(1/8,1/7,1/6)
Extremely strong	(9,9,9)	(1/9,1/9,1/9)
Intermediates	(1,2,3)	(1/3,1/2,1)
	(3,4,5)	(1/5,1/4,1/3)
	(5,6,7)	(1/7,1/6,1/5)
	(7,8,9)	(1/9,1/8,1/7)

Source: (Moslem et al,2019)

b) The Matrix is shown in Eq. 2, where ($\tilde{d}_{ij}^{k}$) indicates the (k^{th}) decision maker's preference of (i^{th}) criterion over (j^{th}) criterion, via fuzzy triangular numbers. Here, "tilde" represents the triangular number demonstration and for the example case, ($\tilde{d}_{12}^{1}$) represents the first decision maker's preference of first criterion over second criterion, and equals to, $\tilde{d}_{12}^{1}$ = (2,3,4)

$$\tilde{A}^k = \begin{bmatrix} \tilde{d}_{11}^k & \tilde{d}_{12}^k & \cdots & \tilde{d}_{1n}^k \\ \tilde{d}_{21}^k & \cdots & \cdots & \tilde{d}_{2n}^k \\ \cdots & \cdots & \cdots & \cdots \\ \tilde{d}_{n1}^k & \tilde{d}_{n2}^k & \cdots & \tilde{d}_{nn}^k \end{bmatrix} \quad (2)$$

c) If there is more than one expert, we use (the geometric mean) and the Matrix is updated as shown in Eq. 3.

$$\tilde{A} = \begin{bmatrix} \widetilde{d_{11}} & \cdots & \widetilde{d_{1n}} \\ \vdots & \ddots & \vdots \\ \widetilde{d_{n1}} & \cdots & \tilde{d}_{nn} \end{bmatrix} \quad (3)$$

d) The geometric mean of fuzzy comparison values of each criterion is calculated as shown in Eq. 4. Here, $\tilde{r}_i$ still represents triangular values.

$$\tilde{r}_i = \left[\prod_{j=1}^{n} \tilde{d}_{ij}\right]^{\frac{1}{n}} \quad (4)$$

e) The fuzzy weights of each criterion can be found with Eq. 5, by incorporating next 3 sub steps:

- Find the vector summation of each $\tilde{r}_i$.
- Find the (-1) power of summation vector. Replace the fuzzy triangular number, to make it in an increasing order.
- To find the fuzzy weight of criterion i ($\tilde{w}_i$), multiply each ($\tilde{r}_i$) with this reverse vector.

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \cdots \oplus \tilde{r}_n) \quad (5$$

$$= (lw_i, mw_i, uw_i)$$

f) Since ($\tilde{W}_i$) are still fuzzy triangular numbers, they need to de-fuzzified by Centre of area method via applying the equation 6.

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \quad (6)$$

g) (M_i) is a non fuzzy number. But it needs to be normalized by Eq. 7.

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \quad (7)$$

h) In order to ensure that the experts 'judgments are consistent, a consistency check must be performed. Therefore, the value of the consistency ratio (CR) must be obtained from the following equation:

$$CR = \frac{CI}{RI} \quad (8)$$

The (CI) (Consistency Index) we get from Equation (9):

$$CI = \frac{{}_{max}\lambda - N}{N - 1} \quad (9)$$

(N) represents the number of items to be compared, (λ_{max}) largest Eigen value of the judgment matrix, (RI) represents (consistency index) for a randomly generated pair wise comparison matrix. Table (5) shows the (RI) values that depend on the number of elements.

Table (5): Random consistency index (RI)

n	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	**1.58**

Source: (Ilangkumaran et al, 2014)

In general, the degree of consistency is acceptable if the CI / RI is less than 0.1, but if this ratio is more than 0.1, it means there are contradictions and therefore the matrix must be repeated.

THE APPLICATION IN THE BOILER

Applying the proposed method to the boiler

In this section, we will explain the steps to apply the proposed method to the failure modes in the boiler system, which is located within the General Company for Textile and Leather Industries. This boiler has an important role in the production processes that take place in the company, its main functions are to generate heat and pressure to complete the production processes in the company, such as medical cotton palace, plaster, gauze and others. This method aims to solve the issue of assessing and ranking the risks of failure modes in the boiler and it consists of the following steps:

a) Identify failure modes, their causes and effects

Through personal interviews with the expert and field visits to the boiler, (8) types of faults that may occur and pose risks have been identified. Table (6) shows the types of failures that have been identified, their causes and their effects in the boiler.

Table (6): failure modes, their causes and effects in the boiler

	Failure modes	**Causes**	**Effect**
1	**Low water level inside the boiler**	**Electrical fault**	**The boiler stops suddenly and the boiler drum may be damage**
2	**Corrosion in boiler inner tubes**	**salts, sediments and heat**	**Low heat pressure**
3	**Failure of the valve and pump of the fuel supply system**	**Electrical fault**	**There is no fire**
4	**Failure forced draft fan**	**Electrical fault**	**There is no fire**

5	**Nozzle failure of the fuel supply system**	**Clogged due to dirt or fuel impurities**	**The boiler stopped**
6	**Failure of the operating lighter**	**Electrical fault or boiler smoke**	**There is no fire**
7	**Fotocellula failure**	**Electrical fault or carbon**	**The boiler stopped**
8	**The boiler does not separate and pressure the steam across the permissible level (7).**	**Electrical fault inside the control panel**	**An internal explosion may occur if a safety valve does not open.**

b) FAHP computation

The FAHP mathematical procedure consists of the following steps:

- **Building a hierarchy**: Here FAHP is applied to FMEA outputs that begin with building a hierarchy of the problem of risk assessment and prioritization. Figure (1) illustrates the hierarchical structure of this evaluation problem.
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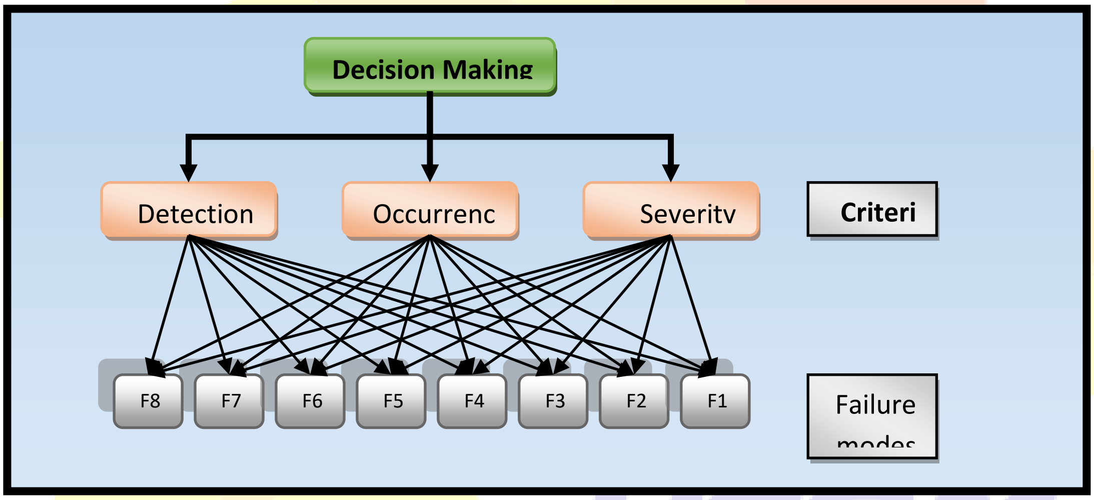

Figure (1): The hierarchical structure of risk assessment

- **Compare risk criteria and obtain weights:** pair wise comparisons are obtained from the expert's judgments for each two criteria separately from the other criteria according to the scale shown in Table (4). Table (7) shows a matrix of fuzzy pair wise comparisons for the risk criteria. In Table (8) the weights of the criteria.

Table (7): Matrix of fuzzy pair wise comparisons for risk criteria

Criteria	Severity			Occurrence			Detection		
Severity	1	1	1	6	7	8	2	3	4
Occurrence	1/8	1/7	1/6	1	1	1	1/5	1/4	1/3
Detection	1/4	1/3	1/2	3	4	5	1	1	1

Table (8): Weights of the Risk Criteria

Criteria	w_i	
Severity	0.6523	λ_{max}= 3.073
Occurrence	0.0793	CI = 0.036
Detection	0.2682	CR = 0.063
Total	1.0000	

- **Compare failure modes for each criterion and obtain the weights:** pair wise comparisons of failure modes are determined for each criterion based on a scale of preference. Table (9) shows the fuzzy pair wise comparisons of the failure modes according to the severity criterion. Table (10) shows the weights of the failures according to the severity criteria in the boiler.

Table (9): Fuzzy comparison matrix for failure modes (Severity)

Severity	F1	F2	F3	F4	F5	F6	F7	F8
F1	1,1,1	3,4,5	3,4,5	4,5,6	5,6,7	9,9,9	6,7,8	2,3,4
F2	1/5,1/4,1/3	1,1,1	3,4,5	2,3,4	4,5,6	6,7,8	5,6,7	1/4,1/3,1/2
F3	1/5,1/4,1/3	1/5,1/4,1/3	1,1,1	1,2,3	3,4,5	3,4,5	1,2,3	1/4,1/3,1/2
F4	1/6,1/5,1/4	1/4,1/3,1/2	1/3,1/2,1	1,1,1	1,2,3	2,3,4	1,2,3	1/4,1/3,1/2
F5	1/7,1/6,1/5	1/6,1/5,1/4	1/5,1/4,1/3	1/3,1/2,1	1,1,1	2,3,4	1,2,3	1/5,1/4,1/3
F6	1/9,1/9,1/9	1/8,1/7,1/6	1/5,1/4,1/3	1/4,1/3,1/2	1/4,1/3,1/2	1,1,1	1/3,1/2,1	1/7,1/6,1/5
F7	1/8,1/7,1/6	1/7,1/6,1/5	1/3,1/2,1	1/3,1/2,1	1/3,1/2,1	1,2,3	1,1,1	1/6,1/5,1/4
F8	1/4,1/3,1/2	2,3,4	2,3,4	2,3,4	3,4,5	5,6,7	4,5,6	1,1,1

Table (10): Weights of failure modes (severity)

Failure Modes	w_i	
F1	0.35	
F2	0.17	
F3	0.09	
F4	0.07	λ_{max}= 8.804 CI = 0.114 CR = 0.081
F5	0.05	
F6	0.02	
F7	0.04	
F8	0.21	
Total	1.00	

c) RPN computation:

After the weights of the risk criteria and the failure modes have been determined, we obtain the value (RPN) of the failure modes according to the proposed method as shown in the table (11) using equation (10):

$$RPN = W(S) * F1(S) + W(O) * F2(O) + W(D) * F3(D) \qquad (10)$$

Where $w(c)$ represents weights of criteria and $F(n)$represents alternative weights.

Table (11): Calculation (RPN) for the failure modes in the proposed method

Failure modes	Severity (0.6523)	Occurrence (0.0793)	Detection (0.2682)	RPN	Ranking
F1	0.35	0.03	0.11	0.262	1
F2	0.17	0.02	0.38	0.213	2
F3	0.09	0.12	0.05	0.081	5
F4	0.07	0.09	0.05	0.065	6
F5	0.05	0.12	0.22	0.099	4
F6	0.02	0.35	0.05	0.056	8
F7	0.04	0.23	0.05	0.057	7
F8	0.21	0.04	0.11	0.166	3
Total	1.000	1.000	1.000	1.000	

Calculating (RPN) in the traditional method:

Here we will get the (RPN) value based on the expert's assessments According to the traditional method, Table (12) shows the expert's ratings for the risk criteria and the RPN values for the failure modes in the boiler by using Eq.1.

Table (12): Calculation (RPN) for the failure modes in the traditional method

Failure modes	Severity	Occurrence	Detection	RPN
F1	9	3	2	54
F2	7	4	6	168
F3	6	5	3	90
F4	5	6	3	90
F5	4	4	5	80
F6	3	8	2	48
F7	3	7	2	42
F8	8	2	2	32

Comparison of the results of the traditional and proposed method

Table (13) shows the results of the traditional and proposed method, where we notice in the traditional method that the two types of fault (3,4) obtained the same value of (RPN) which is (90). Consequently, this similarity leads to difficulty in prioritizing the failure modes and determining which the most dangerous, while are in the proposed method there is no difficulty in determining the priority, in addition to the relative importance of the risk criteria being taken into consideration.

Table (13): Comparison of (RPN) in the traditional and proposed method

Failure modes	FAHP		traditional	
	RPN	Ranking	RPN	Ranking
1	0.262	1	54	4
2	0.213	2	168	1
3	0.081	5	90	2
4	0.065	6	90	2
5	0.099	4	80	3
6	0.056	8	48	5
7	0.057	7	42	6
8	0.166	3	32	7

We notice in Fig. (2) that there are failure modes such as (1,8) whose ranking has decreased in the traditional method, while it is of high risk in the proposed method, due to its low evaluation according to criteria (occurrence and detection). There are also other failures whose priorities have increased in the traditional method, such as (3,4) due to their high evaluation according to (occurrence and detection) criteria.

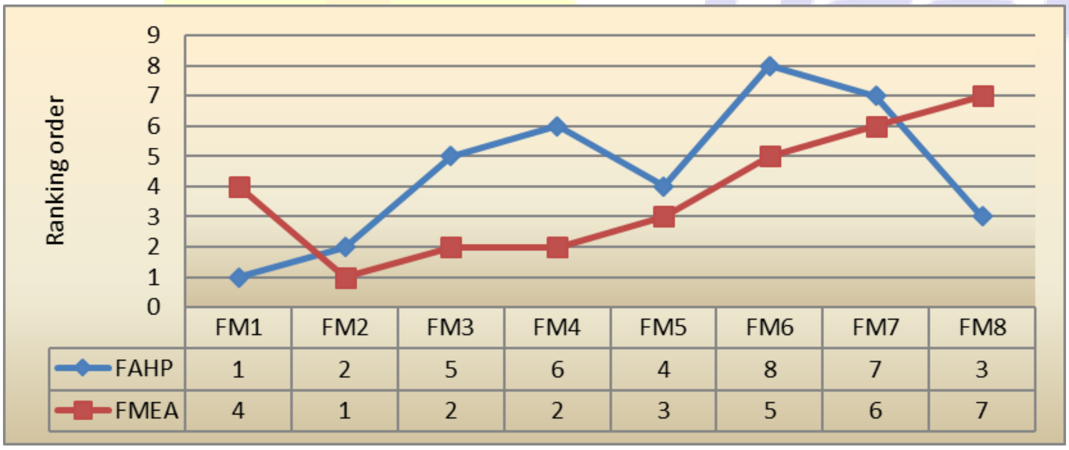

Figure (2): ranking comparison of priority in the traditional and proposed method

CONCLUSIONS

1. The proposed integration method (FMEA-FAHP) was able to identify the failure modes in the boiler section, determine their causes, effects, and current controls for each failure modes, in addition to determining the risk priority of the failure modes.
2. The results showed that there are (8) failures in the boiler, which were ranking according to (RPN) values in the proposed method as follows:
   F1> F2> F8> F5> F3> F4> F7> F6
   In the traditional method as follows:
   F2> F (3, 4)> F5> F1> F6> F7> F8
3. The proposed method can provide the company with an effective tool to deal with known and / or potential risks that may occur in the boiler to increase reliability and safety at work.
4. By comparing the two methods, the results confirmed the weakness of the traditional method in obtaining accurate assessments of the risks of failure modes, while the proposed method was able to overcome the drawback of the traditional (FMEA) and obtain more accurate results.

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