

Article

A New Approach for Failure Modes, Effects, and Criticality Analysis Using ExJ-PSI Model—A Case Study on Boiler System

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Abstract: Failure Modes, Effects, and Criticality Analysis are widely used to assess the failure modes of a system, along with their causes and effects. Several Multi-Criteria Decision-Making approaches have been developed to overcome the limitations of the traditional FMECA. In these approaches, several multiple criteria are considered to determine the criticality values and assign criticality ranks. In these developed approaches, only one expert can involve in criticality analysis. By incorporating several experts from design, manufacturing, and maintenance domains in the criticality analysis accuracy of the results can be improved. This paper proposes a new integrated Expert Judgment-based Preference Section Index (ExJ-PSI) model that combines MCDM approaches and integrates expert opinions. The proposed model is applied to a boiler system used in the textile industry. The results are compared with those obtained from the conventional FMECA and normalized median method. In the present study, the opinions of seven experts from various domains and organizations are discussed. To normalize the collected data, one scale is developed by considering four expert criteria, such as the experience of the expert, the number of boilers he is handling, the number of employees under his supervision, and the proficiency in the field. The proposed model is more effective and flexible in handling and analyzing data of complex configured systems consisting of many subsystems, components, and failure modes. The analysis reveals that the feed water pump, feed water pump motor, supply water temperature sensor, return water temperature sensor, header, and coal feed motor are some of the most critical components of the boiler system.

Keywords: ExJ-PSI model; failure modes; effects and criticality analysis (FMECA); expert judgments; risk priority number (RPN); boiler system; textile industry

1. Introduction

The boiler system is a complex and critical system used in textile industries that works under severe environmental conditions such as temperature, humidity, dust, and vibration levels. The uninterrupted steam supply in the textile process industries mainly depends upon the continuous functioning of the boiler system. To meet this requirement, reliability and maintainability studies of boiler systems, including frequency of failure, failure modes, and their causes and effects, must be carried out. Frequency failure analysis, reliability, and maintainability analysis of a boiler system are presented in [1,2], and are suggested to modify the current maintenance plan to enhance the availability of the boiler system. Therefore to reduce the system failures and implement the new maintenance plan, it is important to consider the components' different failure modes and causes. Failure Modes, Effects, and Criticality Analysis (FMECA) is the most commonly used method for improving maintenance practices. FMECA is a technique used to identify potential failures in product design or process analysis before they occur. FMECA identifies the corrective steps needed to avoid failure and to ensure the system's optimal performance, quality and reliability for the customer. FMECA can be performed during the design or development phase of the product or process.

The criticality of a failure event in conventional FMECA is determined based on the Risk Priority Number (RPN) range. It is usually evaluated by combining three risk factors—Severity (SV), Occurrence (O), and Detection (D). However, few researchers have highlighted some of the significant limitations of the conventional FMECA approaches [3]. Some researchers included only SV, O, and D factors in their study, but a few more risk elements must be included. Also, in many types of research, equal weightage is given to all the risk factors, but it should be different in different cases of risk analysis. In certain cases, SV, O, and D values are different for different failure modes, but the RPN value may be the same for these failure modes. In such cases, the precise value of the risk factor and criticality index is often difficult to calculate. The Multi-criteria Decision Making (MCDM) methods have been developed to overcome these shortcomings of the conventional FMEA process and to improve the effectiveness of risk assessment. The limitations of the conventional FMEA method are often inadequate and unreliable in real cases, particularly when decision-makers are not sure when their decisions are made.

This study related to earlier work on applications of MCDM methodology to improve the efficiency of FMECA. In this regard, Chang et al. [4] used the Fuzzy Gray Rational Analysis (FGRA) method to identify the risk priority of failures. Braglia [5] considered Risk Factors (RF's): severity, occurrence, detection, and failure cost to measure RF value and to identify potential failure modes. Braglia also proposed a fuzzy technique for Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method to prioritize the possible risks in the criticality analysis of failure modes [6]. Seyed-Hosseini [7] used the Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique to highlight the indirect relation between failure modes (FM's) and to provide unique rankings to the FM's. To evaluate critical sub-systems in power plants, considering technological, economic, and sustainability aspects, Chatzimouratidis and Pilavachi [8] used the Analytical Hierarchy Process (AHP) technique. Suebsomran [9] used AHP and FMEA techniques to classify primary failure mode rankings, taking into account risk factors: men working time, maintenance costs, and line priority of the thermal power plant. The potential relationship between the possible causes of failure, taken into account by Zammori and Gabbrielli [10], and the integrated Analytical Network Process (ANP) is used to rank the FMs. Silvestri et al. [11] used the ANP approach to assign weights to traditional risk factors and to improve safety; a multi-criteria risk analysis was carried out in manufacturing systems.

In 2012, Kutlu and Ekmekçioğlu [12] applied fuzzy AHP and Fuzzy TOPSIS techniques to give weight to the conventional risk factors. Singh and Kulkarni [13] used AHP to conduct a criticality analysis of a thermal power plant. RF weights were considered in fuzzy terms [14], and Multiple Objective Optimization based on Ratio Analysis (MULTIMOORA) technique was used to prioritize failure modes. In order to assess the criticality of the failure

modes of the coal-fired thermal power plant, Adhikary et al. [15] presented the Complex Proportional Assessment of alternatives to the Gray relations (COPRAS-G) method based on uncertain data. Liu et al. [16] used the hybrid MCDM approach incorporating AHP, VIKOR, and DEMATEL for the diesel engine turbocharger system. Fuzzy belief structure and TOPSIS approaches were used to normalize incomplete evaluation parameters and prioritize FMs [17]. Liu et al. [18] have used the hybrid TOPSIS approach to compile subjective and objective expert judgments. Hajiagha et al. [3] used the Fuzzy belief structure-based VIKOR method to rank failure modes and risk factors given by experts. Zhou and Thai [19] used a combination of the gray and fuzzy theory to prioritize FMs of tanker equipment.

Liu et al. [20] used a Qualitative Flexible (QUALIFLEX) gray rational analysis method to calculate the relative weights of the risk. Jagtap and Bewoor [21] applied AHP to identify the critical equipment of a thermal power plant. Dempster-Shafer's theory has been suggested by Certa et al. [22] to prioritize the FMs of the fishing vessel system. Huang et al. [23] compared Risk factor rankings by the TODIM method with the conventional RPN and IWF-TOPSIS method. In order to prioritize FMs, Zhao et al. [24] considered risk factors linguistically and combined interval-valued fuzzy set and MULTIMOORA methods were used. Jiang et al. [25] applied the Z-number concept to evaluate RPN and rank FMs of rotor blades of an aircraft turbine. AHP was used to determine the weights of RFs, and the rank of street cleaning vehicle FMs was given using the Fuzzy-TOPSIS (FTOPSIS) method [26]. Tian et al. [27] calculated the relative weights of the RFs by the fuzzy best-worst method. Relative entropy was used to compute the weights of team members, and finally, failure modes were prioritized by the VIKOR method. Fattahi and Khalilzadeh [28] applied fuzzy AHP and MULTIMOORA methods to calculate RF weights and failure modes in the steel industries. The reliability-based rough approach of VIKOR was used to prioritize the RFs of the vertical machining center transmission system [29]. Pancholi and Bhatt [30] used COPRAS-G and PSI methods to calculate the Maintainability Criticality Index (MCI) of each failure mode of an aluminum wire rolling mill. Gugaliya et al. [31] used AHP in the risk criterion weighting assessment, and ERVD was used to rank the FM of process plant induction motors. Javed et al. [32] performed a sensitivity analysis of a multi-generation system, and in [33] performed a 4E analysis of three different configurations of a combined cycle power plant integrated with a solar power tower system to improve its performance.

According to the literature review, a significant amount of effort has been made to improve traditional factor weights and MCDM methodology. FMECA is generally a group decision-making activity, with the members of the FMECA team having different skills and experiences [34]. The various FMECA team members may have ambiguous and incomplete assessment knowledge of FMs [35]. Therefore, for precise assessment, we must collect risk factor information from several team members (experts). However, in work reported earlier, failure information is collected from a single expert only. Precise assessment of the severity of various FMs is a significant challenge that engineers often misunderstand in a real industrial scenario. Faulty assessments lead to the incorrect prioritization of the enterprise according to its risk levels, reducing the reliability and availability of the system and increasing the costs. Incorrect assessment of the criticality of the components may result in the assignment of improper maintenance tasks, increasing the maintenance cost. Keeping in mind the importance of accurate component criticality assessment, we proposed a new integrated, multi-attribute Expert Judgment based Preference Section Index (ExJ-PSI) model to rank failure modes and identify critical components based on their risk levels. The proposed model allows a number of experts to collect accurate risk factor data.

In the conventional FMEA method, failure modes are assessed by a small number of analysts. Most industrial systems are complex and contain a wide number of subsystems. Therefore, it is important to involve several experts from various fields of expertise and from different organizations to achieve a more accurate assessment and evaluation. This paper proposes a new risk priority ExJ-PSI model, based on conflict judgment and the opinions given by a large number of experts, to identify failure modes and critical components. The model presented here enables data collection on numerous failure modes and their risk

variables. This approach is useful for achieving unbiased group assessments, which can easily be accepted and minimized by decision-makers on the final impact of their decisions. A mathematical framework based on scale normalization is then developed to deal with the uncertainty and vagueness of the opinions of various experts in the risk assessment process. The normalized RF values are used to form a decision matrix, and finally, the PSI method is used to estimate the criticality values. Finally, it is used for an effective evaluation of failure modes and critical components of a boiler system to validate the effectiveness and applicability of the developed model.

This paper is structured as follows: the detailed procedure of the developed model is introduced in Section 2. A particular case analysis of the boiler system is then presented in Section 3. It includes detailed failure causes and their effects on the performance, including FMECA of the boiler system. Section 4 discusses the effects of the developed model and its comparison with the conventional FMECA. Finally, Section 5 summarizes the concluding remarks on the proposed model.

2. Framework of the Proposed ExJ-PSI Model

The present study takes six criteria into account: severity of the failure (SV), probability of the occurrence (O), degree of detectability (D), degree of maintainability (M), degree of safety (S), and production or quality loss (L). It is difficult to determine the interdependence of these attributes and to assign importance when determining the criticality of the components. As a result, the Preference Section Index (PSI) approach is utilized to rank the risk priority of FMs properly. The framework of the developed model is presented in Figure 1. It is also specified step-by-step for the convenience of the readers:

- **Step 1:** Select and arrange a set of risk factors and failure modes in the decision matrix.
- **Step 2:** Collect the risk factors rank data from the various experts of several industries.
- **Step 3:** Normalize the data collected by assigning overall weights to experts.
- **Step 4:** Construct initial decision matrix 'A' with criteria ranks,

$$A = [a_{ij}] = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}$$

where a_{ij} is the index value. $i = 1, 2, \dots, m$ along the row represents the failure modes and $j = 1, 2, \dots, n$ represents the risk criteria's along the column.

- **Step 5:** Normalize decision matrix 'A'

Normalization of A is achieved by the following equations [30],

For maximizing attributes,

$$N_{ij} = \frac{a_{ij}}{a_{ijmax}} \quad (1)$$

For minimizing attributes,

$$N_{ij} = \frac{a_{ijmin}}{a_{ij}} \quad (2)$$

where; a_{ijmax} and a_{ijmin} are the maximum and minimum values of each alternative (Criteria). The normalized decision matrix A1 is shown below;

$$A1 = [a_{ij}] = \begin{bmatrix} N_{11} & N_{12} & \dots & N_{1n} \\ N_{21} & N_{22} & \dots & N_{2n} \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ N_{m1} & N_{m2} & \dots & N_{mn} \end{bmatrix}$$

- **Step 6:** Calculate the mean value of the normalized data [30].

$$N = \frac{1}{m} \sum_{i=1}^m N_{ij} \quad (3)$$

- **Step 7:** Calculate the values of the variation of preferences between the values of every attribute [30].

$$\varphi_j = \frac{1}{m} \sum_{i=1}^m (N_{ij} - N)^2 \quad (4)$$

- **Step 8:** Calculate the deviations in the preference value for all criteria [30].

$$\Omega_j = (1 - \varphi_j) \quad (5)$$

- **Step 9:** Calculate the overall criteria weights for each criteria [30].

$$w_j = \frac{\Omega_j}{\sum_{j=1}^n \Omega_j} \quad (6)$$

- **Step 10:** Prepare a matrix by multiplying N_{ij} and w_j .
- **Step 11:** Calculate the Criticality Index for all failure modes and all components. The criticality index of all failure modes can be estimated using Equation (7) [30].

$$CI_{PSI} = \sum_{j=1}^n (N_{ij} \times w_j) \quad (7)$$

Finally, the criticality index of the components can be estimated using Equation (8) [30].

$$(CI_{PSI})_{\text{comp}} = \sum_{i=1}^k (N_{ij} \times w_j) \quad (8)$$

where $i = 1, 2, \dots, k$, are the failure modes of that component or subsystem.

- **Step 12:** Criticality rankings are given by increasing order according to the value of CI_{PSI} , i.e., the higher value of CI_{PSI} has a higher priority.

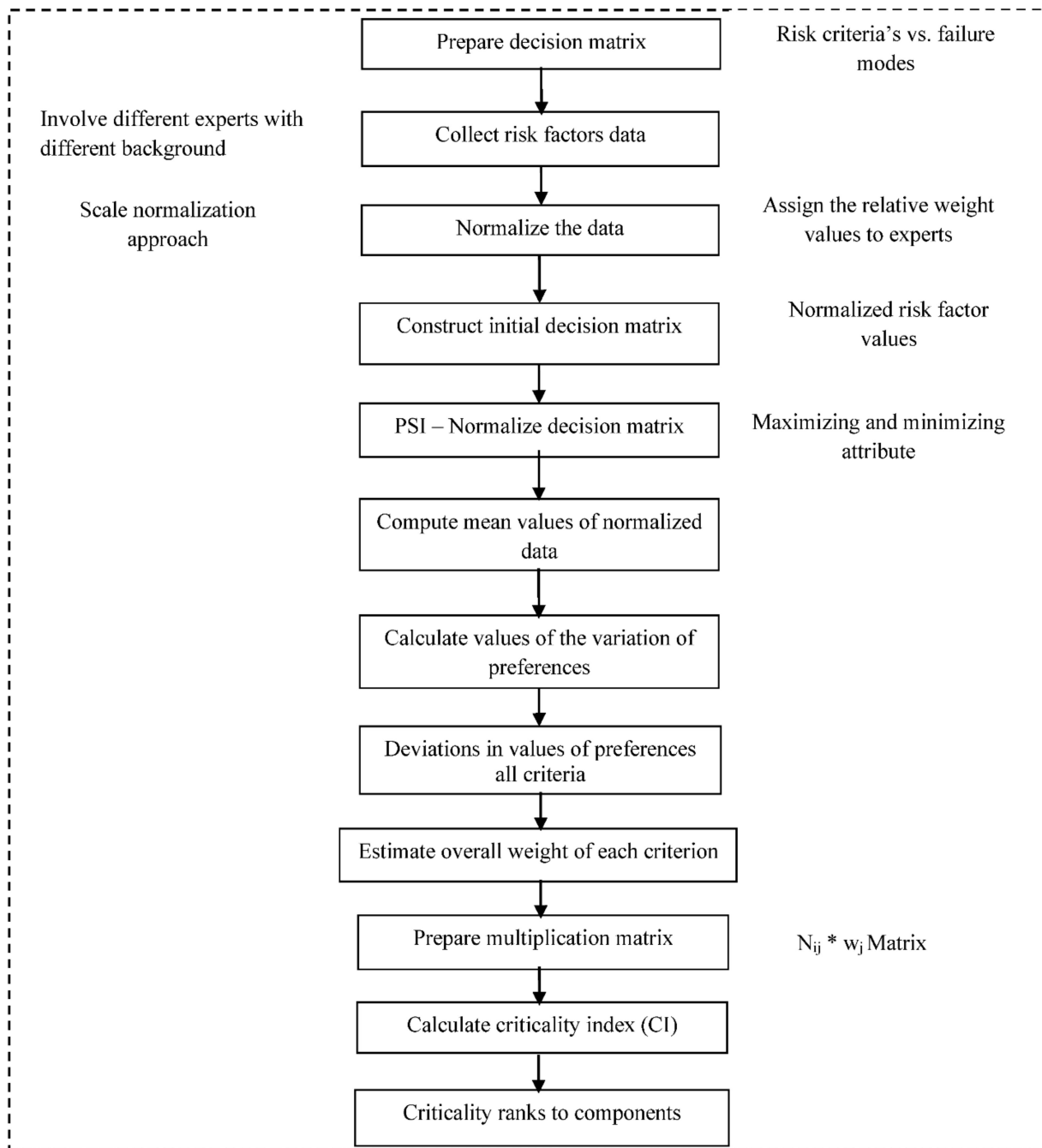


Figure 1. Framework of the integrated ExJ-PSI model.

3. Case Study of Boiler System Used in Textile Process Industries

The boiler system is a complex system with many critical subsystems defined by Patil et al. [36,37] used in the Indian textile industries. Patil et al. [38] presented some critical subsystems through failure frequency analysis of the boiler system and reliability analysis [39]. This section presents a detailed failure analysis of components of the boiler system using the proposed integrated ExJ-PSI model. Data on the components' various failure modes, the failure causes, and their effects on the system's performance, along with the various risk factors that need to be addressed, is collected from industry experts (Appendix A).

- **Step 1:** Select and arrange a set of risk factors and failure modes in the form of a decision matrix.

Each failure mode and cause is assessed based on six different criteria: severity of the failure (SV), probability of the occurrence (O), degree of detectability (D), degree of maintainability (M), degree of safety (S), and production or quality loss (L). The rating scores for each cause of failure are ranked between 1–10 for each criterion. The rating charts for these parameters have been established using the Delphi technique [40]. The risk criteria rating scales for SV, O, D, M, S, and L are shown in Tables 1–6, respectively. Furthermore, these tables assign the score ratings to all failure modes.

- **Step 2:** Collection of the risk factors data

Table 1. FMECA scale to rate severity (SV).

Sr. No	Failure Effect Severity Category	Severity Category Description	Rank
1	Very High	The failure of the boiler system may cause risk to the operator's life with or without warning.	10
2		Failure causes complete system failure or system inoperable.	9
3		The system requires major maintenance, is time-consuming, and incurs very high maintenance costs.	8
4	High	Loss of primary function.	7
5		System performance is degraded.	6
6	Moderate	Moderate effect on system performance.	5
7		The subsystem/component requires major repair, moderate cost of repair.	4
8	Low	Subsystem/component requires minor repair and low maintenance costs.	3
9		Minor effect on system performance.	2
10	Very Minor	Very minor effects or no effect on system performance.	1

Table 2. FMECA scale to rate occurrence (O).

Sr. No	Occurrence Criterion	Ranking Meaning	Possible Failure Rate	Rank
1	Very Frequent	Occurrence is almost certain	Every Month	10
			Between 1 month to 3 months	9
2	Frequent	Failure occurs repeatedly	Between 3 months to 6 months	8
			Between 6 months to 1 Year	7
3	Occasional	Failure occurs occasionally	Between 1 Year to 4 Years	6
			Between 4 Years to 8 Years	5
4	Remote	Few failures expected	Between 8 Years to 10 Years	4
			Between 10 Years to 12 Years	3
5	Extremely unlikely	Occurrence is quite unlikely	Between 12 Years to 15 Years	2
			More than 15 Years	1

Table 3. FMECA scale to rate detection (D).

Sr. No	Detectability	Criteria Meaning	Rank
1	Impossible	The present system is not able to detect failure mode or cause, or there is no control over failure.	10
2	Absolute Uncertain		9
3	Highly Difficult	Very low probability the current monitoring system detects the failure	8
4	Moderately Difficult		7
5	Difficult		6
6	Less Difficult	Possibly detecting the failure.	5
7	Very less Difficult		4

Table 3. *Cont.*

Sr. No	Detectability	Criteria Meaning	Rank
8	Easy to Detect	High probability the current method can detect the failure	3
9	Very easy to detect		2
10	Almost certain	Present method almost certainly detect the failure	1

Table 4. FMECA scale to rate maintenance (M).

Sr. No	Maintenance Criterion	Ranking Meaning for Maintenance	Rank
1	Extensive Damage	Component replacement is required, and the maintenance time required is more than 60 h	9–10
2	Major Damage	Very difficult to repair, and the maintenance time required is between 40 to 60 h	7–8
3	Localized Damage	Difficult to repair, and the maintenance time required is between 20–40 h	5–6
4	Minor Damage	Easy to repair, and the maintenance time required is between 2 to 20 h	3–4
5	Slight Damage	Very easy to repair, and the maintenance time required is less than 2 h	1–2

Table 5. FMECA scale to rate safety (S).

Sr. No	Criterion for Safety	Ranking Meaning	Rank
1	Very High Dangerous	Multiple/Single fatalities	9–10
2	Highly Dangerous	Permanent injury to the operator	7–8
3	Moderate Dangerous	Major physical injury to the operator	5–6
4	Minor Dangerous	No permanent or minor injury to the operator	3–4
5	Very less Dangerous	Failure doesn't affect to human life	1–2

Table 6. FMECA scale to rate production/quality loss (L).

Sr. No	Criterion	Ranking Meaning for Production/Quality Loss	Rank
1	Extensive Loss	The loss is not recoverable. More than 5 days of production loss.	9–10
2	Major Loss	The loss is 50% recoverable. Up to 3 to 5 days of production loss.	7–8
3	Moderate loss	The loss is not wholly recoverable through normal production. Up to 1 to 3 days of production loss.	5–6
4	Minor Loss	Loss is recoverable through normal production. Up to 2 to 24 h of production loss.	3–4
5	Little to no effect	Loss can be easily recovered. Less than 2 h of production loss.	1–2

In order to reduce the uncertainty in assigning the scales, several experts are involved. The risk factors rank data for all components and failure modes is collected from six experts, each with more than ten years of experience in the field of boiler system maintenance. This collected data is then normalized by assigning weights to each expert. However, in order to normalize the ranks given by the experts, four main factors are considered in this research to assign weights to experts: experience in years, number of boilers handling, number of employees under supervision, and proficiency in the field. For each of the selected parameters, different classes have been established. A maximum scale of “5” is allotted to the maximum value, and a minimum scale of “1” is allotted to the minimum value of the selected factors. The scale for the selected parameters is shown in Table 7 for each expert. The relative weight and overall weight values for each of the selected parameters have been estimated by assigning weight values to each expert. The overall weight values of all experts are shown in Table 8.

- **Steps 3 and 4:** Normalize the collected data and construct initial decision matrix ‘A’

Table 7. Scale to assign experts weightage.

Sr. No	Experience in Years	Number of Boilers Handling	Number of Employees under Supervision	Proficiency in the Field	Scale
1	>20	16–20+	10+	Specific Boiler Inspection course and certification	5
2	16–20 Y	11–15	8–10	Highly qualified	4
3	11–15 Y	7–10	5–7	Qualified and Boiler Attendant Course	3
4	5–10 Y	3–6	2–4	Less qualified with Boiler Attendant Course	2
5	<5	<3	<2	Less Educated	1

Table 8. Experts overall weight values.

Expert No	Experience in Years		No of Boilers Handling		No of Employees under Supervision		Proficiency in the Field		Experts Overall Weightage
	Weightage	Relative Weight	Weightage	Relative Weight	Weightage	Relative Weight	Weightage	Relative Weight	
Ex1	2	0.087	2	0.1	5	0.1852	5	0.2381	0.6103
Ex2	3	0.1304	5	0.25	5	0.1852	3	0.1429	0.7085
Ex3	5	0.2174	3	0.15	3	0.1111	2	0.0952	0.5737
Ex4	5	0.2174	3	0.15	2	0.0741	1	0.0476	0.4891
Ex5	2	0.087	1	0.05	3	0.1111	3	0.1429	0.391
Ex6	4	0.1739	4	0.2	5	0.1852	4	0.1905	0.7496

Normalized ranks are estimated for all failure modes by multiplying the experts' ranks and the overall weight value of the expert. The various failure modes and causes of 25 boiler system components are studied. A decision matrix is prepared for the failure modes of all the components using these normalized ranks. Table 9 shows the decision matrix of risk factors for two selected components, water tubes, and a feedwater pump.

- **Step 5:** Results obtained after Normalize decision matrix 'A'

Table 9. Decision matrix A for PSI.

Component	Failure Mode	Failure Cause	Failure Effect	SV	O	D	M	S	L
				Severity	Occurrence	Detection	Maintenance	Safety	Loss
Water Tubes	Short term overheating	Starvation of steam or water flow	Axial fish-mouth rupture	4.25	3.22	2.63	3.29	2.56	3.07
		Blockages from debris	Axial fish-mouth rupture	4.48	3.99	2.67	3.39	2.37	3.24
	Thin lip failure of the tube	Due to rapid heating	Rupture	4.47	3.67	2.86	2.80	2.02	3.34
	Tube joints failure	Dissimilar metal welds	System failure	4.78	3.38	2.63	3.29	2.16	3.20
	Crack and holes	Calcium and magnesium layer increases	The boiler should be closed	5.03	3.45	2.38	3.15	1.93	3.45
	Tube surface corrosion	Due to the presence of moisture content	Tube failure	3.81	2.60	2.51	2.60	1.61	2.65
	Deposits formed in the top of the drum	due to refractory brick deterioration	partially blocking the blowdown channel ports	4.29	3.09	2.30	2.99	2.09	2.78
	Boiler tube blisters/bulges	Due to presence of internal scale	Tube failure	4.94	2.95	2.92	2.66	1.97	3.05

Table 9. Cont.

Component	Failure Mode	Failure Cause	Failure Effect	SV	O	D	M	S	L
				Severity	Occurrence	Detection	Maintenance	Safety	Loss
Feed Water Pump	The strainer failure	The strainer is clogged	Pump Fails	2.67	3.73	1.93	2.38	1.58	2.31
	Rust of tank	A lot of sediment in the water	Failure of mechanical seal and cause a leak	3.11	3.35	1.96	2.96	1.87	2.13
	condensate is too hot for the pump	steam traps fail	Failure of pump's impeller	2.47	3.84	1.90	2.38	1.75	2.15
	mechanical seal failure	Pump leakage	Pump failure	2.70	3.28	2.31	3.21	1.84	2.41
	Electrical failure of the pump	The voltage supplied to the pump is not correct.	Failure of circuit breaker and winding burns	2.89	3.49	2.04	3.21	1.69	1.98
	Impeller Failure	Impeller is clogged	Mechanical failure of pump	2.67	3.13	2.20	3.37	1.45	2.39
	Shaft failure	Overload work, Misalignment, Corrosion	Pump vibration, Pump works but does not provide flow	3.57	3.06	2.16	3.38	1.16	2.44
	Deterioration of the bearings	Lubrication failure	Insufficient flow	2.71	3.16	2.44	3.44	1.42	2.32
		Improper mountings	Pump vibrates or is noisy.	2.71	3.48	2.32	3.10	1.34	2.24
		Abnormal load on motor	Pump failure	3.37	3.24	2.50	3.25	1.28	2.54
		Contamination present	Pump failure	2.25	3.52	2.29	3.33	1.40	2.21
	Pump housing volute damaged/Volute erosion	Cavitation, corrosion and Vibration	Leak in the pump body	2.80	2.92	1.97	3.28	1.56	2.46
	Pump low efficiency	Electric motor failed	Low flow warning	2.63	2.89	2.10	3.18	1.38	2.75
			Low discharge pressure	2.39	2.81	2.22	2.87	1.50	2.15
	Reduction in pump pressure	Pump cavitation	Pump noise and vibration	3.02	2.88	2.31	3.31	1.77	2.04

The value of the attribute must be dimensionless in multi-attribute decision-making methods. For this reason, the attribute value is converted between 0 and 1, which is known as normalization. All six parameters of this analysis are minimization criteria, i.e., lower attribute values are preferred. The normalization of the decision matrix–A is performed by using Equation (2) and the results are shown in Table 10.

- **Step 6:** Compute the mean value of the normalized data.

Table 10. Normalized decision matrix for PSI.

Component	Failure Mode	Failure Cause	Failure Effect	SV	O	D	M	S	L
Water Tubes	Short term overheating	Starvation of steam or water flow	Axial fish-mouth rupture	0.5294	0.8079	0.7238	0.7245	0.4534	0.6446
		Blockages from debris	Axial fish-mouth rupture	0.5026	0.6511	0.7107	0.7028	0.4898	0.6111
	Thin lip failure of the tube	Due to rapid heating	Rupture	0.5034	0.7091	0.6636	0.8500	0.5743	0.5937
	Tube joints failure	Dissimilar metal welds	System failure	0.4709	0.7696	0.7220	0.7238	0.5375	0.6188
	Crack and holes	Calcium and magnesium layer increases	The boiler should be closed	0.4472	0.7533	0.7994	0.7548	0.6005	0.5742
	Tube surface corrosion	Due to the presence of moisture content	Tube failure	0.5900	1.0000	0.7560	0.9148	0.7198	0.7462
	Deposits formed at the top of the drum	Due to refractory brick deterioration	Partially blocking the blowdown channel ports	0.5249	0.8423	0.8279	0.7969	0.5546	0.7127
	Boiler tube blisters/bulges	Due to the presence of an internal scale	Tube failure	0.4552	0.8829	0.6499	0.8942	0.5883	0.6502

Table 10. Cont.

Component	Failure Mode	Failure Cause	Failure Effect	SV	O	D	M	S	L
Feed Water Pump	The strainer failure	The strainer is clogged	Pump fails	0.8432	0.6967	0.9862	1.0007	0.7326	0.8559
	Rust of tank	A lot of sediment in the water	Failure of mechanical seal and cause a leak	0.7227	0.7757	0.9677	0.8031	0.6203	0.9296
	condensate is too hot for the pump	steam traps fail	Failure of the pump's impeller	0.9122	0.6777	1.0018	0.9993	0.6648	0.9224
	mechanical seal failure	Pump leakage	Pump failure	0.8323	0.7919	0.8231	0.7422	0.6310	0.8216
	Electrical failure of the pump	The voltage supplied to the pump is not correct.	Failure of circuit breaker and winding burns	0.7776	0.7457	0.9337	0.7414	0.6864	1.0008
	Impeller Failure	Impeller is clogged	Mechanical failure of the pump	0.8416	0.8316	0.8643	0.7062	0.8009	0.8296
	Shaft failure	Overload work, misalignment, corrosion	Pump vibration, pump works but does not provide flow	0.6300	0.8492	0.8783	0.7041	1.0029	0.8131
	Deterioration of the bearings	Lubrication failure	Insufficient flow	0.8292	0.8224	0.7782	0.6915	0.8159	0.8547
		Improper mountings	Pump vibrates or is noisy.	0.8308	0.7471	0.8178	0.7673	0.8657	0.8833
		Abnormal load on the motor	Pump failure	0.6683	0.8033	0.7615	0.7327	0.9098	0.7811
		Contamination present	Pump failure	1.0022	0.7383	0.8303	0.7147	0.8286	0.8959
	Pump housing volute damaged/Volute erosion	Cavitation, corrosion and vibration	Leak in the pump body	0.8041	0.8899	0.9628	0.7252	0.7436	0.8038
	Pump low efficiency	Electric motor failed	Low flow warning	0.8550	0.8997	0.9055	0.7476	0.8426	0.7204
			Low discharge pressure	0.9421	0.9242	0.8552	0.8283	0.7759	0.9231
	Reduction in pump pressure	Pump cavitation	Pump noise and vibration	0.7446	0.9017	0.8243	0.7198	0.6560	0.9690

The mean values of the normalized data for each risk factors are calculated using Equation (3) and are as follows;

$$N_{SV} = 0.7069, N_O = 0.8048, N_D = 0.8280, N_M = 0.7820, N_S = 0.6998, N_L = 0.7894.$$

- **Step 7:** Calculate the values of the variation of preferences.

In this step, preference variation values for all risk factors are calculated using Equation (4), and its values are $\varphi_{SV} = 0.0287$, $\varphi_O = 0.0072$, $\varphi_D = 0.0097$, $\varphi_M = 0.0080$, $\varphi_S = 0.0190$, $\varphi_L = 0.0158$.

- **Step 8:** Calculate the deviations in the value of preference for all criteria.

Deviations in the preference values for all the risk factors are calculated by using Equation (5), and its values are $\Omega_{SV} = 0.9713$, $\Omega_O = 0.9928$, $\Omega_D = 0.9903$, $\Omega_M = 0.9920$, $\Omega_S = 0.9810$ and $\Omega_L = 0.9842$.

- **Step 9:** Calculate the overall criteria weights for all criteria.

The overall criteria weights for all risk factors are computed by Equation (6), and their values are $w_{SV} = 0.1643$, $w_O = 0.1679$, $w_D = 0.1675$, $w_M = 0.1678$, $w_S = 0.1659$ and $w_L = 0.1665$.

- **Step 10:** Results obtained after preparing a matrix by multiplying N_{ij} and w_j .

In this step, the overall risk factors matrix is prepared by multiplying N_{ij} and w_j . Table 11 shows the multiplication matrix of N_{ij} and w_j .

- **Step 11:** Calculate the criticality index for all components, and finally, ranks are given.

Table 11. Multiplication matrix of N_{ij} and w_j .

Component	Failure Mode	Failure Cause	Failure Effect	SV	O	D	M	S	L
				$N_{ij} \times w_j$	$N_{ij} \times w_j$	$N_{ij} \times w_j$	$N_{ij} \times w_j$	$N_{ij} \times w_j$	$N_{ij} \times w_j$
Water Tubes	Short term overheating	Starvation of steam or water flow	Axial fish-mouth rupture	0.0870	0.1356	0.1212	0.1216	0.0752	0.1073
		Blockages from debris	Axial fish-mouth rupture	0.0826	0.1093	0.1190	0.1179	0.0813	0.1017
	Thin lip failure of the tube	Due to rapid heating	Rupture	0.0827	0.1191	0.1112	0.1426	0.0953	0.0989
	Tube joints failure	Dissimilar metal welds	System failure	0.0774	0.1292	0.1209	0.1215	0.0892	0.1030
	Crack and holes	Calcium and magnesium layer increases	The boiler should be closed	0.0735	0.1265	0.1339	0.1267	0.0996	0.0956
	Tube surface corrosion	Due to the presence of moisture content	Tube failure	0.0969	0.1679	0.1266	0.1535	0.1194	0.1242
	Deposits formed at the top of the drum	Due to refractory brick deterioration	Partially blocking the blowdown channel ports	0.0862	0.1414	0.1387	0.1337	0.0920	0.1187
	Boiler tube blisters/bulges	Due to the presence of an internal scale	Tube failure	0.0748	0.1482	0.1089	0.1500	0.0976	0.1083
Feed Water Pump	The strainer failure	The strainer is clogged	Pump fails	0.1385	0.1170	0.1652	0.1679	0.1215	0.1425
	Rust of tank	A lot of sediment in the water	Failure of mechanical seal and cause a leak	0.1187	0.1302	0.1621	0.1348	0.1029	0.1548
	Condensate is too hot for the pump	Steam traps fail	Failure of the pump impeller	0.1499	0.1138	0.1678	0.1677	0.1103	0.1536
	Mechanical seal failure	Pump leakage	Pump failure	0.1367	0.1330	0.1379	0.1245	0.1047	0.1368
	Electrical failure of the pump	The voltage supplied to the pump is not correct	Failure of circuit breaker and winding burns	0.1278	0.1252	0.1564	0.1244	0.1139	0.1666
	Impeller failure	Impeller is clogged	Mechanical failure of the pump	0.1383	0.1396	0.1448	0.1185	0.1329	0.1381
	Shaft failure	Overload work, misalignment, corrosion	Pump vibration, pump works but does not provide flow	0.1035	0.1426	0.1471	0.1181	0.1664	0.1354
		Lubrication failure	Insufficient flow	0.1362	0.1381	0.1303	0.1160	0.1354	0.1423
	Deterioration of the bearings	Improper mountings	Pump vibrates or is noisy	0.1365	0.1254	0.1370	0.1288	0.1436	0.1471
		Abnormal load on the motor	Pump failure	0.1098	0.1349	0.1276	0.1229	0.1509	0.1301
		Contamination present	Pump failure	0.1647	0.1240	0.1391	0.1199	0.1375	0.1492
	Pump housing volute damaged/Erosion	Cavitation, corrosion and vibration	Leak in the pump body	0.1321	0.1494	0.1613	0.1217	0.1234	0.1338
	Pump low efficiency	Electric motor failed	Low flow warming	0.1405	0.1511	0.1517	0.1254	0.1398	0.1199
			Low discharge pressure	0.1548	0.1552	0.1432	0.1390	0.1287	0.1537
	Reduction in pump pressure	Pump cavitation	Pump noise and vibration	0.1223	0.1514	0.1381	0.1208	0.1088	0.1613

The criticality index values for all the failure modes are estimated using Equation (7). Finally, the criticality index of the components can be estimated by summing the criticality index values of all the failure modes of the component.

A similar analysis was carried out for all 124 failure modes of the 25 selected boiler system components. Finally, the criticality ranks of the components are given based on their criticality index values, and the results of all 25 selected components of the boiler system are shown in Table 12. There are several root causes for some of the failure modes. However, prominent root causes are considered for the study. The criticality index values and their ranks for a few selected boiler sub-systems are also presented in Table 12.

Table 12. Criticality Index and their criticality ranks of boiler sub-systems and components.

Sub-Systems	Component	Overall CI of Component	Criticality Rank	Overall CI of Sub-System	Criticality Rank
Combustion and Ignition System	Furnace	1.5559	22	13.7475	2
	Shell	2.1224	19		
	Header	5.1139	6		
	Intake vent/Air vent	1.8910	21		
	Combustion chamber	3.0643	10		
Feed Water Supply System	Water tubes	5.3936	3	49.953	1
	Supply water temperature sensor	5.2401	4		
	Backflow preventer valve	2.7529	12		
	Temperature regulator	2.7632	11		
	Feed water pump motor	6.5052	2		
	Feed water pump	12.2870	1		
	Strainer	2.7128	13		
	Feed water tank	4.4311	9		
	Water level controller	1.0964	25		
	Feed water hose	2.2889	18		
	Water softner	2.0131	20		
	Deaerator	2.4687	15		
Blow-down System	Return water temperature sensor	5.2306	5	9.0564	3
	Drain pump	2.5268	14		
	Condensate filter	1.2990	24		
Emission Control System	Induced Draft (ID) fan	2.3364	17	8.1287	4
	Forced Draft (FD) fan	4.4738	8		
	Mechanical dust collector (MDC)	1.3185	23		
Fuel Supply System	Burner	2.3683	16	7.3796	5
	Feed motor	5.0113	7		

4. Results and Discussion

This section compares the conventional FMECA method and the developed ExJ-PSI model to demonstrate the effectiveness of the proposed model. However, a literature review shows that many MCDM methods were developed to improve the effectiveness of FMECA. However, most of them cannot handle complex systems [41]. Therefore, involving a large group of experts is necessary to solve the complex systems of FMECA. The developed ExJ-PSI model considers the parameters affecting the operational safety and cost features in actual industrial applications. The developed model allows a large number of experts in the analysis and considers different kinds of uncertainty in experts' judgments. Guerrero and Bradley [42] stated that the average and median individual scores also perform better than the group consent method. Therefore, the final results of the FMECA of the boiler system by the proposed method, normalized median method, and conventional FMECA method are

compared in Table 13 and Figure 2. This study shows the impact of the other risk criteria like maintenance time, safety, and operational loss on the components' criticality.

Table 13. Comparative analysis by Proposed Model, Conventional RPN, and Normalized Median method.

Component	Rank by Proposed Model	Conventional RPN Method	Normalized Median	Component	Rank by Proposed Model	Conventional RPN Method	Normalized Median
Feed Water Pump	01	03	01	Drain pump	14	10	16
Feed Water Pump motor	02	08	02	Deaerator	15	12	15
Supply Water Temperature Sensor	03	02	05	Burner	16	05	14
Return Water Temperature Sensor	04	01	06	Induced Draft (ID) Fan	17	17	13
Header	05	07	07	Feed water hose	18	06	12
Feed Motor	06	04	04	Shell	19	24	10
Forced Draft (FD) Fan	07	14	08	Water Softner	20	21	21
Feed Water tank	08	11	09	Intake vent/Air vent	21	20	22
Water Tubes	09	09	03	Furnace	22	23	20
Combustion Chamber	10	19	11	Mechanical dust collector (MDC)	23	25	24
Temperature regulator	11	16	19	Condensate filter	24	18	25
Back flow preventer valve	12	22	17	Water level controller	25	13	23
Strainer	13	15	18				

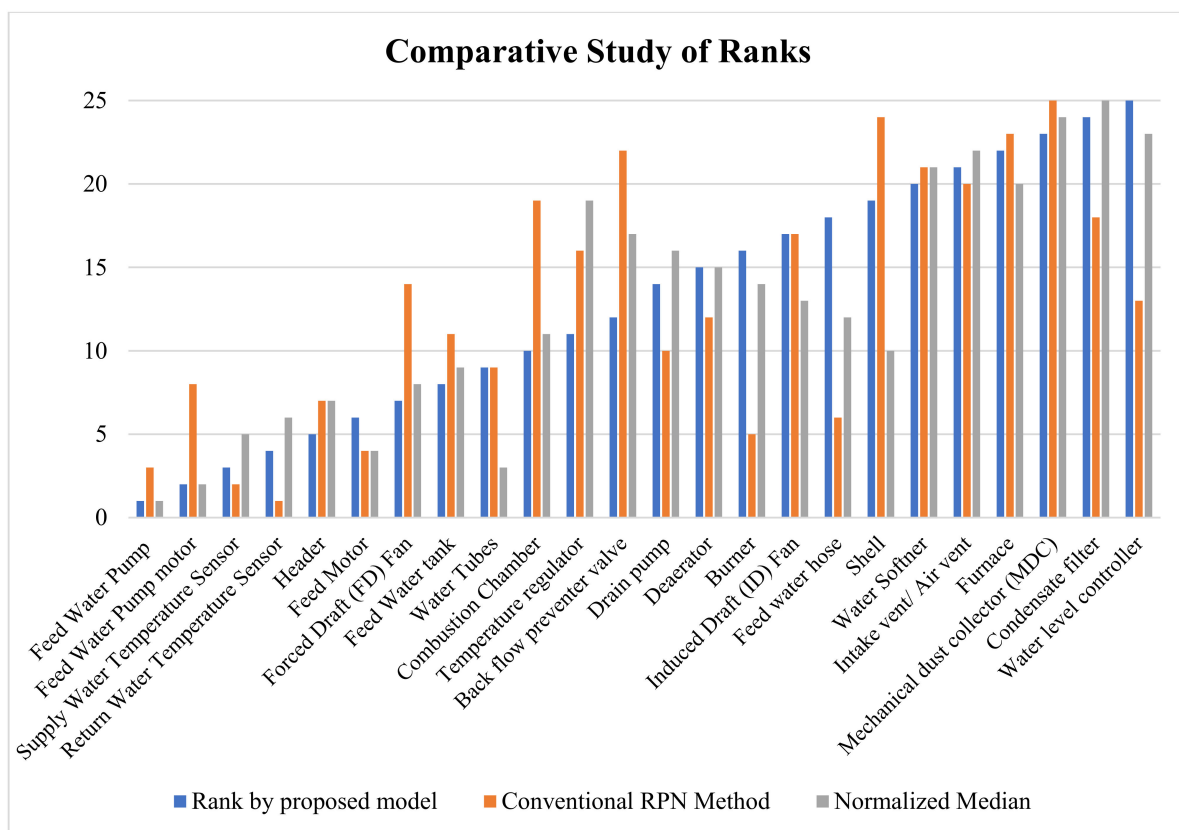


Figure 2. The histogram of the component rankings of the boiler system by conventional method and proposed model.

The discrepancy between the FMECA proposed, and the traditional FMECA are compared. From Figure 2, the ranking orders of the boiler system components have slightly deviated. This is because the proposed FMECA resolves many of the problems in the conventional FMECA, such as not considering vagueness and subjectivity in decision-making and enhancing consistency by including a large number of experts. Moreover, the ranks given by the proposed method and the normalized median method are similar and slightly deviated in some cases, which shows that the proposed ExJ-PSI model is effective.

5. Conclusions

In this paper, we developed a novel ExJ-PSI model for the analysis of complex systems that integrates the FMECA method and an integrated preference section index (PSI) approach to reduce the limitations of the conventional FMECA method. It reduces the uncertainty and vagueness in the risk assessment process and also improves the effectiveness of the traditional FMECA. The accuracy of the developed method is enhanced by collecting data from a number of experts. A case study on a boiler system validates the practicability and effectiveness of the developed model. The conclusions from the comparative study of the ExJ-PSI model, normalized median method, and the conventional FMECA method are;

- It is required to consider various additional risk criteria, such as operational and maintenance time, human safety, and operational loss, to improve the effectiveness of the analysis.
- Normalizing the rankings given by a large group of experts minimizes its uncertainty due to varying work experience and skills.
- The preference section index (PSI) method uses the concept of statistics instead of weight attribute allocations in another multi-criteria decision-making (MCDM) approach and thus is observed to be more effective while deciding the relative importance when a conflict situation occurs.
- The effectiveness of the model is validated over the conventional FMECA for the case of complex systems such as boilers, and it is found very useful in prioritizing failure modes to minimize the overall losses effectively due to sudden breakdown.

It is observed from this research that the feedwater pump is the most critical component of the boiler system, having several critical failure modes, such as impeller failure, shaft failure, and deterioration of the bearings, leading to a complete replacement with high cost and maintenance time needed. Furthermore, the feedwater pump motor is ranked second and justified because maintenance is longer when the bearing is worn out, and the armature is seized. However, according to the conventional FMECA, the feedwater pump and feedwater pump motor ranking were three and eight, respectively, i.e., less critical. This shows that the maintenance time and cost, production loss, and safety impact the component's criticality. Similarly, in conventional FMECA, the rank of the water level controller was thirteen, and according to the proposed model, it is twenty-five, which indicates it is significantly less critical. The failure of the water level controller may affect the water tubes; therefore, its rank in conventional FMECA was high. However, the effect of its failure on production loss and maintenance or replacement cost is significantly less, so it comes in less critical according to the proposed model. The criticality rankings of the components in the proposed FMECA model are, therefore, more precise than those of the traditional FMECA when we consider additional criteria such as maintenance cost, production loss, and safety.

In the traditional FMECA method, when the values of SV, O, and D are the same, the RPN will be the same, and they are assumed to have the same priority numbers. However, in reality, the two failure modes would have different O and D values. Moreover, there are many failure modes to the components, some of which do not affect SV, O, and D but the safety, maintenance time/cost, and quality. Therefore, different experts must assess failure modes to deal with this issue. They act in different roles in the risk analysis process, as they come from different fields and have different knowledge and experience. The analysis reveals that the feed water pump, feed water pump motor, supply water temperature

sensor, return water temperature sensor, header, and coal feed motor are identified as some of the most critical components of the boiler system. The drain pump, deaerator, burner, induced draft (ID) fan, feed water hose, and water softener are some of the medium critical components, and the intake air vent, mechanical dust collector (MDC), condensate filter, and water level controller are the less critical components of the boiler system.

This paper considers six criteria for failure analysis while deciding the critical components of the boiler system. However, criteria such as operator skills, operating environmental conditions, age of equipment, mean time between failures (MTBF), economic loss and maintenance costs, etc., can also be considered. Nevertheless, an improved FMECA model can be exploited for other process industries.

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Appendix A

Table A1. Failure modes, Causes and Effects of the selected components of the boiler system.

Boiler Components	Failure Mode	Failure Cause	Failure Effect
Furnace	Short term overheating	Starvation of steam or water flow	Axial fish-mouth rupture
	Furnace plate bulged	Due to internal steam pressure	System failure
	Layer of hardness scale over the tubes	Poor quality water supply	Slipping of hardness to boiler
Shell	Shell plate bulging due to scale formation	The feed water hardness was not monitored properly	Boiler shell failure can result in catastrophe
	Shell burst	Lamellar tear in raw material	Boiler shell failure can result in catastrophe
	Shell burst	By cyclic stresses	
	Shell burst	Due to Improper weld	
Header	Deposition	Inadequate blow-down control	System failure
		Poor chemical feed control	System failure
	Poor pH control	Downtime corrosion	System failure
		Poor boiler feed water quality	System failure
	Header corrosion due to Oxygen Pitting	Poor mechanical derator performance	System failure
		Downtime corrosion	System failure
		Oxygen in-leakage	System failure
		Scavenger underfeed	System failure
Intake vent/Air vent	Air vent fails to open and close	Corrosion due to gases in the air	Reduces steam pressure, Reduces heat transfer rates and productivity
	Trap malfunctioning	Presence of air in steam lines	Affects on process timing and quality of steam
Combustion Chamber	Incorrect burner sequence	Faulty flame detector	Production stopping
	Too much fuel being fired	Irregularities in flame patterns	Production stopping
	Too much excess air trapped	Blockages in air or fuel flow	Lower production
	Uneven combustion	Clogged fuel nozzles	High temp. on combustor wall can spall the chamber
	High emissions	High temperature in the primary zone high NOx	Incomplete combustion leading to increasing temp and system failure

Table A1. Cont.

Boiler Components	Failure Mode	Failure Cause	Failure Effect
Water Tubes	Short term Overheating	Starvation of steam or water flow	Axial fish-mouth rupture
		Blockages from debris	Axial fish-mouth rupture
	Thin lip failure of tube	Due to rapid heating	Rupture
	Tube joints failure	Dissimilar metal welds	System failure
	Crack and holes	Calcium and magnesium layer increases	Boiler should closed
	Tube surface corrosion	Due to presence of moisture content	Tube failure
	Deposits formed at the top of drum	Due to refractory brick deterioration	Partially blocking the blow down channel ports
	Boiler tube blisters/bulges	Due to presence of internal scale	Tube failure
Supply Water Temperature Sensor	Incorrect signal from sensor element	Reduced signal level	Potential processing error
		Impedance mismatch	
		A/D conversion error	
	Loss of signal from sensor element	Chip failure	Loss of signal to processor
		Corroded sensor	
	Power supply loss of voltage	power supply malfunction	Loss of signal to processor
Back flow preventer valve	Jam and closed	Software error	Potential system malfunction
		Error in algorithm	
	Jam and closed	Dirt and corrosion	No water supply
	Fails to open	Corrosion and power loss	False trip and component failure
Temperature regulator	Coil open	Electrical and surge	False trip
	Coil Short	Corrosion and wire	False trip
	Short	Electrical failure	No cooling
	Open continuous	Electrical and surge	false trip
Feed water Pump- Motor	Fail to operate	Electrical failure	System effect
		Electrical failure/aging	Equipment failure
	Unstable response	Poor lubrication	Noisy
		Overloading	Heat build-up
		Contamination	Stator seized
		High temperature	
		Insulation stator/rotor fails	
	Electrical windings open or short	Excessive high temperature	Motor will not run
			Sparkling at brushes
	Armature cracked	Fatigue	Armature seized or rubbing stator
		Misalignment	
		Bearing failure	
Feed Water Pump	The strainer failure	The strainer is clogged	Pump Fails
	Rust of tank	A lot of sediment in the water	Failure of mechanical seal and cause a leak
	condensate is too hot for the pump	steam traps fail	Failure of pump impeller
	Mechanical seal failure	Pump leakage	Pump failure
	Electrical failure of pump	The voltage supplied to the pump is not correct	Failure of circuit breaker and winding burns
	Impeller failure	Impeller is clogged	Mechanical failure of pump
	Shaft failure	Overload work, misalignment, corrosion	Pump vibration, pump works but does not provide flow
	Deterioration of the bearings	Lubrication failure	Insufficient flow
		Improper mountings	Pump vibrates or is noisy
		Abnormal load on motor	Pump failure
		Contamination present	Pump failure
	Pump housing volute damaged/Volute Erosion	Cavitation, corrosion and vibration	Leak in the pump body
	Pump low efficiency	Electric motor failed	Low flow warning
			Low discharge pressure
	Reduction in pump pressure	Pump cavitation	Pump noise and vibration

Table A1. Cont.

Boiler Components	Failure Mode	Failure Cause	Failure Effect
Strainer	Strainer clogging	Due to dust and dirt and improper cleaning	Water flow problem
	Channeling	High differential pressures flow	Circulation of unfiltered
	Fatigue cracks	Cyclic flow	Fluid
	Media migration	Vibration or cyclic flow	Release of filter media
Feed Water tank	Oxygen pitting	Poor mechanical derator performance	Equipment failure
		Downtime corrosion	
		Poor boiler feed water quality	
	Deposition	Inadequate blowdown control	Equipment failure
	Improper water supply	Workers unawareness	Boiler system failure
	Rust/corrosion	Dust or impurities enters	Tank failure
Water level controller	Leak	Corrosion	Lost water and quality of water
	Fails to operate	Due to corrosion	Boiler failure and hazardous to operator
	Fails to provide signal	Electrical failure	
Feed water hose	Hose Block	Impurities present in water	Insufficient water supply to boiler
	Hose leakage	The shell of the fitting was crimped too much or too little during assembly	Many parts get corroded
	The fitting has blown off the hose	The hose was not inserted deeply enough	Hazardous to operators
	Hose is hard and brittle	The hose was exposed to heat exceeding the maximum recommended temperature	Chance of hose failure
Water Softner	Fail to operate	Water contamination	Scaling and damage of boiler tubes
	No softening	Excess scaling	Reduction in boiler efficiency and production
	Too much softening		Premature boiler failure
Deaerator	Deaerator spray zone corrosion on SS shell	Due to high chlorides	Boiler system failure
	Deaerator inlet header spray pipe failure	Due to high pressure and temp	
	Excessive derator venting	Deaerator steam supply PRV stuck open	Steam pressure low /wastage of steam
	Deaerator spray valve spring failure	Due to excess pressure	Derator failure
ReturnWater Temperature Sensor	Incorrect signal from sensor element	Reduced signal level	Potential processing error
		Impedance mismatch	
		A/D conversion error	
	Loss of signal from sensor element	Chip failure	Loss of signal to processor
		Corroded sensor	
	Power supply loss of voltage	power supply malfunction	Loss of signal to processor
Drain pump	Calibration error	Software error	Potential system malfunction
		Error in Algorithm	
	Drain hose leakage	Due to corrosion, dust and dirt	System failure
	Drain hose blockage	Dirt and corrosion	Inefficient drainage
	Pump gear wear	Material defect	Pump failure
Condensate filter	Strainer is clogged	Improper cleaning	Pump failure
	Internal leakage	Due to aging	Equipment failure
	Clogging	Due to impurities and operators unawareness	System failure
Induced Draft (ID) Fan	Motor or contactor failure	Dust and dirt particles	Loss of control of parameters- temp.
	Fan failure/fails to start	Electrical or mechanical failure	System level effect
	Failure due to jamming of blades	Due to foreign material and dust	Equipment Failure
	De-function or pressure drop	Due to aging	Affects system performance

Table A1. Cont.

Boiler Components	Failure Mode	Failure Cause	Failure Effect
Forced Draft (FD) Fan	Fan operate with high vibration level	Bearing fails	Equipment damage/failure
		Housing wear	
		Unbalanced fan blade	
	Corrosion	Aging	Equipment failure
	Physical damage	Crash	
	Foreign material build up	Lack of cleaning	
Mechanical dust collector (MDC)	Noise in motor	Motor bearing failure	Low production due to fatigue to operator
	Leakage	Due to corrosion	Equipment failure
	Blockage	Due to lack of cleaning	Equipment failure
Burner	Oil gas burner failure	Dust and dirt particles enters in to burner	Boiler stops functioning
	Faulty flame sensor	Manufacturing defect	Chances of furnace explosion if unburnt coal moisture entered in furnace
	High furnace pressure	Failure of PRV	Steam pressure and temperature increases
	Low combustion air	Variation in drum level	Required pressure and temp not obtain
Feed Motor	Open or shorted winding	Excessively high temperature	Motor will not run
	Worn bearing	Poor lubrication	Noisy
		Contamination	Seized
		Overloading or high temperature	Heat build up
	Cracked housing	Fatigue, external shock and vibration	Leakage, shorted or seized
	Sheared armature shaft	Fatigue	Seized
		Misalignment	Armature rubbing stator
		Bearing failure	Motor failure

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