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A MODIFIED FMEA APPROACH BASED INTEGRATED DECISION FRAMEWORK FOR OVERCOMING THE PROBLEMS OF SUDDEN FAILURE AND ACCIDENTAL HAZARDS IN TURBINE AND ALTERNATOR UNIT

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Abstract. *The proposed work presents a novel integrated decision framework, based on Intuitionistic Fuzzy (IF) - Failure Mode & Effect Analysis (IF-FMEA), and IF-Technique for Order of Preference by Similarity to Ideal Solution (IF-TOPSIS) approaches for analysing the failure risk issues of Turbine and Alternator Unit (TAU) in a chemical treatment-based sugar process industry. The proposed novel IF-FMEA approach-based modelling overcomes various demerits of traditional FMEA approaches, which are faced during the identification of critical failure causes based on the Risk Priority Number (RPN) outputs. On the basis of detailed qualitative information related to plant operation, FMEA sheet was developed and linguistic ratings were collected against three risk factors such as probability of Occurrence (O), Severity (S), and Detection (D). IF-Hybrid Weighted Euclidean Distance (IFHWED) score has been computed to rank all listed failure causes under three risk factors. The ranking results based on IF-FMEA approach has been compared with the well existed IF-TOPSIS approach for evaluating the accuracy of the proposed modelling results. Sensitivity analysis has also been done to check the robustness of the framework. The analysis results were provided to the maintenance executives of the TAU unit in order to frame the optimal maintenance plan for overcoming the problems of sudden breakdown. The analysis results are also applicable to TAU systems, which are installed in other chemical process industries globally.*

Key words: *Sugar process industry, IF-FMEA, IF-TOPSIS, Failure causes, Sudden breakdown, Maintenance schedule*

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1. INTRODUCTION

TAU is one of the crucial functionary units, especially in all chemical process industries like petrochemical, fertilizer, paper and pulp, and chemically treated sugar industry, etc. In order to fulfil the power and heat requirement for various processing stages (heating, atomization, cleaning, sterilization, moisturization, humidification, drying, etc.) failure free operation of TAU system is highly important. To ensure the failure free operation of industrial system, like TAU, over long duration, development of an optimum maintenance strategy is needed. For the development of an optimum maintenance schedule, recognising most critical failure causes of different subsystem/component are of supreme importance [1,2]. Furthermore, due to availability of vague operational data from different sources like mill maintenance log book and maintenance personnel of the considered system, the job of system analyst for identifying riskier failure causes with high accuracy has become highly challenging. In order to resolve this task, the development of a mathematical model, which could cover the uncertainty/vagueness in the operational data of a system, proves to be very useful in the identification of critical failure causes with high accuracy, and thus leads to development of correct maintenance policy. IF-modelling based concept proves to be useful in considering the uncertainty/vagueness of the collected data and, hence, results in highly accurate outputs.

In chemical process industries, TAU system is required to operate 24×7 hours as it is commonly used to drive all rotating equipment such as pumps, compressors, etc., and supply heat to heat exchangers, evaporators and ovens. Even a minor failure in the TAU system results in an interruption in the continuous functioning of all these components/subsystems, thus causing a sudden failure in the plant. Therefore, for ensuring continuous functioning of the considered TAU system, each and every associated component/subsystem must function in the most upstage conditions, for which various modes of failure are responsible for sudden failure/breakdown. Failures can be caused, namely, by abrasion, corrosion, electrical pitting, fatigue, overheating, inclusion of foreign particles in oil, and chemical attack of reactive agents (electrolytes/ organic acids) must be addressed with high accuracy [3]. Around 50% of sudden failures of turbines are due to inclusion of contamination of moisture, dirt, etc., in the lubrication systems [4,5]. In a TAU system, improper functioning of a lubrication system often takes place even due to a minor failure of its component/subsystem, which may lead to system's unavailability or poor operational safety, especially when TAU system is used in the chemical process industries. As TAU is one of the important functionary unit responsible for continuous and safe operation of different chemical process industries, in considering its importance in the context of accidental safety and loss prevention, it is indispensable to analyse the operational risk issues associated with the considered unit.

2. LITERATURE BACKGROUND

Over the past few years, scholars have presented many works to diagnose failure causes and study risk- related issues in various process industries and services sectors – geothermal power plant [6], marine industry [7], anaesthesia process [8], health care industry [9], gas processing plant [10], hydraulic turbine generator system [11], cogeneration power plant [12], etc. Liu et al. [13] proposed hybrid fuzzy FMEA - VIsekriterijumska optimizacija i KOm-promisno Resenje (VIKOR) – Decision MAking

Trial and Evaluation Laboratory (DEMATEL) – Analytic Hierarchy Process (AHP) approaches to perform risk analysis of a turbocharger. Panchal and Kumar [14] proposed FMEA to detect the riskier components of a Power Generating Unit (PGU) under uncertainty. Adar et al. [15] implemented fuzzy FMEA for finding the critical failure modes of a Water Gasification System (WGS). Ahn et al. [16] proposed fuzzy-based FMEA to present a risk analysis of liquefied hydrogen tankers to encounter the uncertainties involved in crisp based FMEA. Failure risk analysis of transmission system of an automobile industry was conducted to study the unavailability of considered system [17]. FMEA often provides the basis of Multi Criteria Decision Making (MCDM) approaches, and is applied in combination with MCDM approaches. Also, various limitations associated with the traditional FMEA approach are well covered with the incorporation of MCDM approaches into FMEA approach. Considering this advantage, a new fuzzy FMEA-based extended MULTIple Multi-Objective Optimization by Ratio Analysis (MULTIMOORA) – AHP was introduced by Fattahi and Khalilzadeh [18], and application of the framework was illustrated for a steel factory. Panchal et al. [19] addressed the shortcomings of the IF-THEN rule based fuzzy FMEA approach, and proposed an integrated framework with introduction of an improved FMEA approach, for identifying the riskier failure causes of a chlorine gas plant. Boral et al. [20] proposed application of various fuzzy MCDM, such as Interval Type-2 Fuzzy DEMATEL and Modified Fuzzy Multi-Attribute Ideal Real Comparative Analysis (FMAIRCA) methods within a fuzzy FMEA domain, to encounter the risk relevant to gearbox of a power plant. Gopal and Panchal [21] proposed a fuzzy FMEA approach-based integrated framework for prioritizing the most critical components on the basis of rank of failure causes in a milk process plant. Fuzzy based risk analysis approaches have the drawback that it does not take into account the element of hesitation inherent in the qualitative feedback obtained by the experts. Intuitionistic Fuzzy Set (IFS) concept-based techniques overcome this shortcoming of fuzzy theory approach by considering the hesitation element. With a paradigm shift in uncertainty theory concept, researchers incorporated the IFS concept in FMEA and MCDM techniques-based risk model to achieve a high degree of correctness of results in decision-making approaches. Moreover, the application of IF based hybrid MCDM techniques has increased encapsulating a wide range of modifications and applications. Wang et al. [22] presented a hybrid interval-valued based MCDM approach to perform a risk analysis of hospital service under IF environment. Baig et al. [23] proposed Full Consistency Method (FUCOM) and Fuzzy Quality Function Deployment (QFD) to identify capabilities, which confirm protection against the vulnerabilities involved in oil supply chain. Muhammad et al. [24] proposed grey EDAS approach to select the best alternatives for treatment of waste in Nigeria. Efe [25] proposed an integrated framework based on QFD and VIKOR approach for risk assessment based on FMEA of a ship building industry under the intuitionistic fuzzy environment. Kushwaha et al. [26] applied IFWA operator based FMEA approach identify the riskier components of cutting system by implementing FMEA approach under IF environment. Ilbahar et al. [27] applied FMEA-AHP approaches to access the risk involved in the investment of renewable energy utilising IF concept.

From the above reviewed literature, it is clear that the fuzzy set theory has been applied for analysing the risk involved in various industrial systems. The implemented fuzzy based risk models were insufficient to consider high level of vagueness/

uncertainties involved in the qualitative data/information collected from expert judgement. Due to its limitation of not considering the non-determinacy or hesitation, the results are highly uncertain/inaccurate. Therefore, to overcome this gap, IF- modelling based novel integrated framework has been proposed in this work for studying and analysing the risk issues of TAU in a sugar mill industry.

3. Newly Proposed Integrated Framework

In the first phase, FMEA sheet containing various subsystem/components, its potential mode of failures, effect, failure causes, and linguistic variables under O, S, D, has been generated on the basis of feedback obtained from three mill's personnel within the IF-FMEA approach. In the second phase, the IF-TOPSIS approach has been incorporated into the IF-FMEA approach for tabulating a relative coefficient score based ranking results. Sensitivity analysis was done to evaluate the robustness of the proposed integrated framework. The sequential steps of two-phase integrated decision framework are as shown in Fig. 1.

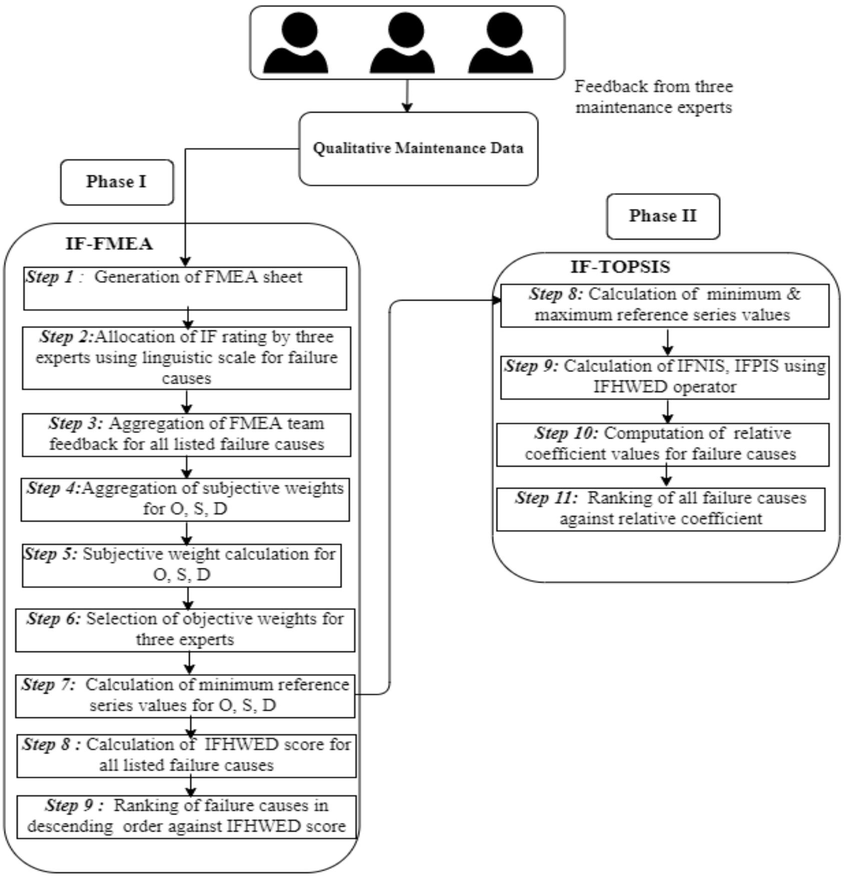

Fig. 1 Two-phase integrated decision framework

4. BASIC IFS NOTIONS AND RISK APPROACHES

4.1 Basic IFS notions

The various notions, which are used in developing the proposed integrated framework, are discussed as follows [28, 29]

Definition 1: An IFS is given by Eq. (1) as:

$$\bar{A} = \left\{ \prec x, \mu_{\bar{A}}(x), \vartheta_{\bar{A}}(x) \succ x \in X \right\} \tag{1}$$

where $\mu_{\bar{A}}(x)$ is a membership function and $\vartheta_{\bar{A}}(x)$ is a non-membership function given by Eqs. (2) and (3) and both must lie in the closed interval [0,1].

$$\mu_{\bar{A}} : S \to [0,1], x \in X \to \mu_{\bar{A}}(x) \to [0,1] \tag{2}$$

$$\vartheta_{\bar{A}} : S \to [0,1], x \in X \to \vartheta_{\bar{A}}(x) \to [0,1] \tag{3}$$

IFS must satisfy the following condition:

$$\mu_{\bar{A}}(x) + \vartheta_{\bar{A}}(x) \leq 1 \text{ for all } x \in X \tag{4}$$

Definition 2: Degree of indeterminacy/ hesitation is defined by Eq. (5)

$$\pi_{\bar{A}}(x) = 1 - \mu_{\bar{A}}(x) + \vartheta_{\bar{A}}(x) \tag{5}$$

Definition 3: Intuitionistic Fuzzy Distance (IFD) between two Intuitionistic Fuzzy Number (IFN) is computed by Eq. (6).

Let $\beta_1 = (\mu_1, \nu_1)$ and $\beta_2 = (\mu_2, \nu_2)$ are two IFNs, then IFD between β_1 and β_2 is given as

$$d_{ifd}(\beta_1, \beta_2) = |\beta_1, \beta_2| = \frac{1}{2}(|\mu_1 - \mu_2| + |\vartheta_1 - \vartheta_2|) \tag{6}$$

4.2 IF-FMEA approach

FMEA is one of the most extensively applied preliminary investigation techniques used in industrial systems to detect the riskier components. It has proved to be an effective and efficient measure in tabulating the failure risk associated with different systems like oxygen combustor system [30], water Treatment Plant [31], water gasification system [15], liquefied natural gas unloading facility [32], power distribution industry [33], milk processing process plant [34], gas refinery [35], electro-chemical industry [36]. The FMEA approach so applied by different researchers is very useful for listing the detailed qualitative information related to operation of a system, due to which it has widely gained importance in studying the failure risk, but this approach has several limitations as identified by different researchers [31,21,36]. To overcome the demerits noted by these scholars, a novel IF-FMEA modelling has been developed for conducting the risk analysis. The novel IF-FMEA modelling encapsulates membership and non-membership functions together, along with indeterminacy/ hesitation element in expert's judgement for a high degree of accuracy in diagnosing the critical failure causes of an industrial system. With a trait to address the indeterminacy/hesitation using membership and non-membership function, the proposed IF-FMEA modelling prove to be highly effective in comparison to other FMEA approaches. The steps followed in carrying IF-FMEA are:

Step 1: Generate FMEA sheet for the TAU subsystem considering all the failure causes under O, S, and D.

Step 2: Using Tables 1-3 allocate IF ratings to all failure causes listed for TAU system.

Table 1 Linguistic terms for Occurrence (O)

Linguistic terms	Failure Probability	IFNs
Very Low (VL)	Rare failure	0.25,0.70
Low (L)	Failure occurs seldom	0.30,0.60
Medium Low (ML)	Few failures	0.40,0.50
Medium (M)	Failure occurs often	0.50,0.50
Medium High (MH)	Almost every time	0.60,0.30
High (H)	Failure occurs every now and then	0.70,0.20
Very High (VH)	Very frequently	0.75,0.20

Table 2 Linguistic terms for Severity (S)

Linguistic terms	Failure Probability	IFNs
Unaffected (UA)	System remains continue in operation without much affecting the production	0.15,0.80
Very Low (VL)	System unavailability with little damage	0.25,.70
Low (L)	Loss of raw material	0.30,0.60
Medium (M)	System operable with little low quality of finished product	0.40,0.50
Medium High (MH)	System operable with lower grade of finished product	0.60,0.30
High (H)	System has to stop for few hours.	0.70,0.20
Very High (VH)	System has to stop which leads to much loss of production	0.75,0.20
Very Very High (VVH)	Entire System has to halt	0.80,0.1

Table 3 Linguistic terms for Detection (D)

Linguistic terms	Failure Probability	IFNs
Almost Uncertain (AU)	Failure is unrecognized	0.10,0.90
Uncertain (UC)	Almost not sure	0.15,0.80
Very Remote (VR)	Very Inaccessible to find	0.20,0.75
Remote(R)	Inaccessible	0.25,0.70
Very Low (VL)	Very low possibility	0.30,0.60
Low(L)	Low possibility	0.40,0.50
Moderate (M)	Medium possibility	0.50,0.50
Medium High (MH)	Medium high possibility	0.60,0.40
High(H)	Recognized	0.65,0.30
Very High (VH)	Highly recognized	0.70,0.20
Certain(C)	Sure	0.80,0.10

Step 3: Applying Eqs. (7) to (9) aggregate an FMEA expert's feedback associated with the set of listed failure causes of the considered system.

$$\delta_{ijO} = IFWA(\delta_{ij1}^{O}, \delta_{ij2}^{O} \ldots\ldots \delta_{ijl}^{O}) = \sum_{k=1}^{l} \psi_k \cdot \delta_{ij}^{O} = \left[1 - \prod_{k=1}^{l} \left(1 - \mu_{ij}^{O}\right)^{\psi_k}, \prod_{k=1}^{l} \left(\vartheta_{ij}^{O}\right)^{\psi_k}\right] \tag{7}$$

$$\delta_{ijS} = IFWA(\delta_{ij1}^{S}, \delta_{ij2}^{S} \ldots\ldots \delta_{ijl}^{S}) = \sum_{k=1}^{l} \psi_k \cdot \delta_{ij}^{S} = \left[1 - \prod_{k=1}^{l} \left(1 - \mu_{ij}^{S}\right)^{\psi_k}, \prod_{k=1}^{l} \left(\vartheta_{ij}^{S}\right)^{\psi_k}\right] \tag{8}$$

$$\delta_{ijD} = IFWA(\delta_{ij1}^{D}, \delta_{ij2}^{D} \ldots\ldots \delta_{ijl}^{D}) = \sum_{k=1}^{l} \psi_k \cdot \delta_{ij}^{D} = \left[1 - \prod_{k=1}^{l} \left(1 - \mu_{ij}^{D}\right)^{\psi_k}, \prod_{k=1}^{l} \left(\vartheta_{ij}^{D}\right)^{\psi_k}\right] \tag{9}$$

where $i=1,\ldots m;\ j=1,\ldots.n$; ψ_k are weights of relative importance of FMEA experts (summation of weights should be less than equal to one); *IFWA* is the Intuitionistic Fuzzy Weighted Averaging (IFWA) operator; δ_{ijO}, δ_{ijS}, and δ_{ijD} are the aggregated IFNs for failure causes under O, S, and D, respectively; δ_{ij}^{O}, δ_{ij}^{S}, δ_{ij}^{D} are the IFNs against linguistic terms according to experts' opinion for failure causes under three risk factors.

Step 4: Using Table 4 aggregate the expert's opinion for subjective weights for O, S, and D as per Eqs. (10) to (12).

Table 4 Linguistic terms for rating the three risk factors

Linguistic terms	Failure Probability	IFNs
Very low (VL)	(0.1,0.85)	Very low (VL)
Low (L)	(0.25,0.7)	Low (L)
Moderate (M)	(0.5,0.5)	Moderate (M)
High (H)	(0.75,0.2)	High (H)
Very high (VH)	(0.9,0.05)	Very high (VH)

$$k_1 = IFWA(k_{j1}^O, k_{j2}^O......k_{ji}^O) = \sum_{k=1}^{i} \psi_k \cdot k_j^O = \left[1-\prod_{k=1}^{i}\left(1-\mu_j^O\right)^{\Psi_k}, \prod_{k=1}^{i}\left(\vartheta_j^O\right)^{\Psi_k}\right] \tag{10}$$

$$k_2 = IFWA(k_{j1}^S, k_{j2}^S......k_{ji}^S) = \sum_{k=1}^{i} \psi_k \cdot k_j^S = \left[1-\prod_{k=1}^{i}\left(1-\mu_j^S\right)^{\Psi_k}, \prod_{k=1}^{i}\left(\vartheta_j^S\right)^{\Psi_k}\right] \tag{11}$$

$$k_3 = IFWA(k_{j1}^D, k_{j2}^D......k_{ji}^D) = \sum_{k=1}^{i} \psi_k \cdot k_j^D = \left[1-\prod_{k=1}^{i}\left(1-\mu_j^D\right)^{\Psi_k}, \prod_{k=1}^{i}\left(\vartheta_j^D\right)^{\Psi_k}\right] \tag{12}$$

$j=1,....n$; k_1, k_2, k_3 are the aggregated subjective opinions for O, S, D; k_j^O, k_j^S, k_j^D, are the experts opinion in form of IFNs against risk factors.

Step 5: Using Eqs. (13) and (14) compute the subjective weights values for O, S, D.

$$\overline{\omega}_j = \frac{\mu_j + \pi_j\left(\dfrac{\mu_j}{\mu_j + \vartheta_j}\right)}{\sum_{j=1}^{n}\left\{\mu_j + \pi_j\left(\dfrac{\mu_j}{\mu_j + \vartheta_j}\right)\right\}} \quad j = 1,....n \tag{13}$$

$$\pi_j = 1 - \mu_j - \vartheta_j \tag{14}$$

$\overline{\omega}_j$ are the subjective weights (for O, S, D), satisfying the condition $\sum_{j=1}^{n}\overline{\omega}_j = 1$.

Step 6: Select the objective weights values for (n=3) for O, S, D from Table 5 as defined by Xu [37].

Table 5 Selection criteria for objective weight

Sr. No	(n) No of experts	Mean (μ)	Standard deviation (σ)	Orness (w)	Disp (w)	Objective weight $(\bar{O}_j)$
1	2	1.5	0.5	0.5	0.6391	(0.5,0.5)
2	3	2	$\sqrt{2/3}$	0.5	0.8473	(0.243,0.514,0.243)
3	4	2.5	$\sqrt{5/4}$	0.5	1.3122	(0.1550, 0.3450, 0.3450, 0.1550)

Step 7: Develop reference series under O, S, D for minimum value using Eq. (15).

$$\tilde{r}_1^- = (r_1^-, r_2^-, \ldots\ldots, r_n^-) = (r^-, r^-, \ldots\ldots, r^-) \tag{15}$$

Step 8: Using Eq. (16) compute IFHWED score values.

$$d_i = IFHWED\left(\tilde{r}_i, \tilde{r}^-\right) = \phi\sqrt{\left[\sum_{j=1}^{m} \bar{\omega}_j \left\{d_{ifd}\left(\delta_{ij}, \delta^-{}_j\right)\right\}^2\right]} + (1-\phi)\sqrt{\left[\sum_{j=1}^{m} \bar{O}_j \left\{d_{ifd}\left(\delta_{i\sigma(j)}, \delta^-{}_{\sigma(j)}\right)\right\}^2\right]} \tag{16}$$

$i=1,\ldots.m$, where, $\bar{O}_j$ is the objective weight value derived from Table 6; d_i is the IFHWED score for the failure causes; ϕ is the restriction coefficient.

Step 9: Rank all the failure causes of system against IFHWED score in the order of decreasing magnitude.

4.3 IF- TOPSIS approach

TOPSIS was first proposed by Hwang and Yoon in 1981 [38]. It is a well-established and extensively applied MCDM approach. The various traits of TOPSIS approaches are (i) very simple in applying under various sets of conflicting criteria, (ii) measures of the relative performance of failure causes with simple mathematical formulations, and (iii) high computational accuracy, which makes this method more and more versatile. Fuzzy TOPSIS and IF-TOPSIS approaches were applied by many researchers in various fields- foundry industry [2], tribological process [39], loader selection [40], sugar mill industry [41], smartphones selection [42], working condition assessment [43], etc. Moreover, Positive Ideal Solution (PIS), Negative Ideal Solution (NIS) and relative coefficient scores are calculated to rank the listed failure causes in TOPSIS approach. Over the time, mathematical uncertainties concepts like fuzzy and intuitionistic fuzzy were incorporated in crisp based TOSIS approach to cover uncertainties/vagueness/hesitations in the expert's domain of knowledge. In this work, IF-TOPSIS approach is incorporated within the IF-FMEA approach due to its ability to provide ranking results based on minimum and maximum reference series values, which proves to be very useful for testing the novel IF-FMEA approach-based results. In IF-TOPSIS, the first seven steps to compute the ranking are similar to IF-FMEA modelling based approach, and hence these steps are not repeated here. The remaining steps involved in IF-TOPSIS approach are as follows:

Step 8: Develop minimum and maximum reference series value using Eqs. (17) and (18) respectively.

$$\tilde{r}_1^- = (r_1^-, r_2^-, \ldots.., r_n^-) = (r^-, r^-, \ldots.., r^-) \tag{17}$$

$$\tilde{r}_1^+ = (r_1^+, r_2^+, \ldots.., r_n^+) = (r^+, r^+, \ldots.., r^+) \tag{18}$$

Step 9: Tabulate IF-NIS and IF-PIS values using Eqs. (19) and (20), respectively.

$$\begin{aligned} R_i^- = IFHWED\left(\tilde{r}_i, \tilde{r}^-\right) &= \phi\sqrt{\left[\sum_{j=1}^{m} \bar{\omega}_j \left\{d_{ifd}\left(\delta_{ij}, \delta^-{}_j\right)\right\}^2\right]} \\ &+(1-\phi)\sqrt{\left[\sum_{j=1}^{m} \bar{O}_j \left\{d_{ifd}\left(\delta_{i\sigma(j)}, \delta^-{}_{\sigma(j)}\right)\right\}^2\right]} \\ &i = 1,\ldots..m \end{aligned} \tag{19}$$

$$\begin{aligned} R_i^+ = IFHWED\left(\tilde{r}_i, \tilde{r}^-\right) &= \phi\sqrt{\left[\sum_{j=1}^{m} \bar{\omega}_j \left\{d_{ifd}\left(\delta_{ij}, \delta^+{}_j\right)\right\}^2\right]} \\ &+(1-\phi)\sqrt{\left[\sum_{j=1}^{m} \bar{O}_j \left\{d_{ifd}\left(\delta_{i\sigma(j)}, \delta^+{}_{\sigma(j)}\right)\right\}^2\right]} \\ &i = 1,\ldots.m \end{aligned} \tag{20}$$

Step 10: Compute relative coefficient score (χ^+) of all the listed failure cause using:

$$\chi^+ = \frac{R_i^-}{R_i^+ + R_i^-} \tag{21}$$

Step 11: Rank all the failure causes against relative coefficient outputs.

5. INDUSTRIAL CASE STUDY- APPLICATION OF THE PROPOSED INTEGRATED FRAMEWORK

5.1 IF-FMEA modelling based results

The proposed integrated framework is illustrated with its application to carry risk analysis of a TAU in a sugar mill industry, geographically located in the western Uttar Pradesh, India. TAU is the most important unit, which fulfils the electricity demand of mill machinery. The schematic arrangement of the TAU is shown in Fig. 2.

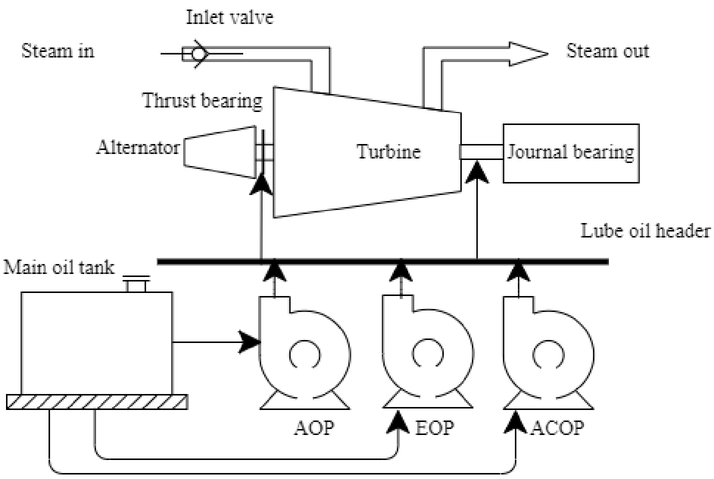

Fig. 2 Schematic arrangement of TAU

A preliminary investigation was conducted with three maintenance experts of TAU for detailed preparation of FMEA sheet. The FMEA sheet consists of all the listed components, potential mode of failure, effect of failure, and failure causes. On the basis of the designed linguistic rating scales (Table 1-3) for O, S and D, the experts were invited to put the linguistic ratings on the basis of knowledge/experience, which is given in Table 6.

Table 6 FMEA sheet

SL NO	Components	Potential mode of failure	Effect of failure	Failure cause	O	S	D
1	Rotor of Turbine	Increase in wheel chamber pressure	Vibration in rotor	Scaling on rotor (RT1)	MH	VH	H
	Blades	Crack due to prolong operation	Low power generation	Scaling (RT2)	M	H	VL
				Corrosion (RT3)	L	H	VL
2	Solenoid valve	Deposition of sediments	Hamper turbine safety	Wearing of piston (SV4)	M	MH	M
				Wearing of diaphragm (SV5)	ML	MH	H
				Loose electrical connection (SV6)	M	H	VH
3	Thrust and journal bearing	Rise in temperature	Tripping of turbine	Rise in temperature of Cooling water (TJ7)	L	H	VH
				Rise in lube oil	M	VH	VH

				temperature (TJ8)			
				Rise in ambient temperature (TJ9)	L	MH	C
				Sintering (TJ10)	M	H	R
4	Pumps						
	Auxiliary Oil Pump (AOP)	Supply failure	Stop supply oil to turbine gear	Electrical fault (AP11)	MH	H	VH
	Emergency Oil Pump (EOP)	Pressure drops	Stop back up to AOP	Battery discharge (AP12)	M	VH	VL
	Auxiliary Control Oil Pump (ACOP)	Pressure drops	Poor lubrication	Unhealthy electrical connections (AP13)	M	H	VH
5	Valves						
	Emergency Stop Valve (ESV)	Drop in pressure of lube oil	Turbine Trips	Stop oil supply (ES14)	L	H	M
	Quick Control Non-Return Valve (QCNRV)	Leakage	Back flow of steam	Gland scaling (ES15)	L	H	L
	Grid valve	Leakage	Performance of mill is affected	Gland leakage (ES16)	L	H	L
6	Main oil pump (MOP) & throttle valve	Pressure drops	Low lubrication of turbine parts	Poor quality of lubricating oil (MP17)	M	H	VL
				Contamination entrapped (MP18)	M	H	R
				Gland leakage (MP19)	L	H	L
7	Alternator rotor	Loud vibrations from bearings	Hamper the operation of alternator	Mechanical fault (OT20)	M	M	C
				Poor bearing lubrication (OT21)	MH	M	VH
	Armature winding	Deterioration of winding	Low emf generation	High temperature (OT22)	M	VH	VH
8	Oil tank & valves	Leakage	Loss of supply of oil	Poor welding (OV23)	H	M	C
				Low grade of material (OV24)	H	H	L
				Gland leakage (OV25)	M	MH	M
				Seat rupture (OV26)	L	H	H

9	Pump	Leakage	Poor cooling of winding	Mechanical & electrical fault (PP27)	L	VH	VH
				Impeller failure (PP28)	M	VH	VH
				Bearing housing failure (PP29)	M	H	C
				Gasket rupture (PP30)	VH	VH	C
				Overheating of motor (PP31)	M	H	C

Here, the first expert has twenty years of experience, second expert seven, while the third expert has four years of experience in the field of operation and maintenance of the TAU unit. The feedback obtained from only the first expert is given in Table 6 due to space limitation. Taking the weights of three experts as ψ_1=0.4, ψ_2 =0.3, ψ_3=0.25 on the basis of their experience, aggregated IFNs values for the set of listed failure causes were tabulated as per Eqs. (7) to (9), and the aggregated IFNs values for all failure causes of the turbine rotor (RT1) under O, S, D are given in Table 7.

Table 7 Aggregated IFNs values for set of failure causes listed under RT

Failure cause	$\boldsymbol{\delta}_{ijO}$		$\boldsymbol{\delta}_{ijS}$		$\boldsymbol{\delta}_{ijD}$	
	$\boldsymbol{\mu}_{ij}$	$\boldsymbol{\vartheta}_{ij}$	$\boldsymbol{\mu}_{ij}$	$\boldsymbol{\vartheta}_{ij}$	$\boldsymbol{\mu}_{ij}$	$\boldsymbol{\vartheta}_{ij}$
RT1	0.4763	0.4457	0.7323	0.1823	0.6938	0.2144
RT2	0.4734	0.4648	0.6983	0.2168	0.2965	0.6162
RT3	0.4399	0.4900	0.6983	0.2168	0.4212	0.5000

Using the same equations and experts' weights, aggregated IFNs values for the other set of failure causes listed under different subsystem/component of TAU were computed. Due to space constraints, these calculations are not shown here. Using the linguistic scale (Table 4), responses from the three experts were obtained for calculating subjective weights for O, S, and D and are given in Table 8.

Table 8 Linguistic ratings, Aggregated IFNs and subjective weights against O, S, D

Risk Factor	Occurrence (O)	Severity (S)	Detection (D)
Linguistic ratings	VL, L, M	VH, H, H	VH, H, M
Subjective weights	0.1538	0.4320	0.4142

Using the feedback-based values from Table 8 in Eqs. (10-12), the aggregated subjective IFN values for O, S, and D were calculated but sample calculation only for O is shown here:

$$k_1 = \left\{1-(1-0.1)^{0.4}\times(1-0.25)^{0.3}\times(1-0.5)^{0.25}\right\}, \left\{(0.85)^{0.4}\times(0.7)^{0.3}\times(0.5)^{0.25}\right\}$$
$$= \{0.2605, 0.7080\}$$

Using the calculated aggregated subjective IFN values, the values of degree of indeterminacy is calculated using Eq. (14). Using the above calculated IFNs in Eq. (13), subjective weights calculation for the risk factors O is given below (other subjective weights are calculated in same manner). All the subjective weights are given in Table 8.

$$\overline{\omega}_1 = \frac{0.2605+0.0315\times\left(\frac{0.2605}{0.2605+0.7080}\right)}{0.2605+0.0315\times\left(\frac{0.2605}{0.2605+0.7080}\right)+0.8143+0.0612\times\left(\frac{0.8143}{0.8143+0.1245}\right) +0.7713+0.0648\times\left(\frac{0.7713}{0.7713+0.1639}\right)} = 0.1538$$

Using Table 5, appropriate objective weights were selected according to the three experts as 0.234, 0.514, and 0.234. As per Eq. (15), reference series under O, S, and D, for the minimum series value, were established for the set of listed failure causes under different subsystem using IFD operator and aggregated IFNs values (Table 7). A sample calculation for the reference series of turbine rotor, RT1 (first failure cause) under O is computed as:

$$\left\{d_{ifd_O}(0.4763, 0.4775)\right\} = \frac{1}{2}\left\{(|0.4763-0|)+(|0.4775-1|)\right\} = 0.7534$$

Similarly, the reference series under other risk factors and other listed failure causes were calculated, but are not shown here, and the reference series matrix was generated for the set of failure causes of the turbine rotor RT as:

$$\tilde{r}^{-}_{RT1} = \begin{bmatrix} RT_1 \\ RT_2 \\ RT_3 \end{bmatrix} = \begin{bmatrix} 0.7534 & 1.1412 & 1.0866 \\ 0.7410 & 1.0900 & 0.4884 \\ 0.6949 & 1.0900 & 0.6712 \end{bmatrix}$$

Reference series matrices for other set of failure causes of TAU components are tabulated in the same manner. Lastly, IFHWED scores values were calculated for each listed failure causes, using the reference series values and taking the restriction constant value $\phi = 0.6$ for subjective weights (Table 8), and the objective weights (Table 5) in Eq. (16). For illustration, sample calculation for tabulating the IFHWED score for RT1 is given as:

$$d_{RT_1} = 0.6\sqrt{0.1538\times0.7534^2+0.4320\times1.1412^2+0.4142\times1.0866^2} +$$
$$(1-0.6)\sqrt{0.243\times0.7534^2+0.514\times1.1412^2+0.243\times1.0866^2} = 1.0588$$

Similarly, IFHWED scores (d_i) for all other listed failure causes were calculated, and ranking has been done against IFHWED scores, as shown in Table 9.

Table 9 Failure causes, IFHWED score, IFFMEA based Rank, IF-NIS, IF-PIS, relative coefficient and IF-TOPSIS based Rank

Failure causes	IIFHWED score	IF-FMEA based Rank	IF-NIS	IF-PIS	Relative coefficient	IF-TOPSIS based Rank
RT1	1.0588	1	0.2121	0.4736	0.6910	1
RT2	0.8590	3	0.5851	0.7346	0.5390	3
RT3	0.8940	2	0.4568	0.6619	0.5746	2
SV4	0.8953	2	0.3950	0.6324	0.5860	2
SV5	0.9030	1	0.3526	0.6042	0.5991	1
SV6	0.8799	3	0.4227	0.6403	0.5788	3
TJ7	1.0811	1	0.1986	0.4662	0.6987	1
TJ8	0.9908	2	0.2705	0.5383	0.6480	2
TJ9	0.8829	3	0.4611	0.7150	0.5525	3
TJ10	0.8228	4	0.6224	0.7648	0.5183	4
AP11	1.0439	1	0.2089	0.4704	0.6893	1
AP12	0.8549	3	0.6158	0.7514	0.5322	3
AP13	0.8799	2	0.4227	0.6403	0.5788	2
ES14	0.9794	1	0.3298	0.5895	0.6243	1
ES15	0.8529	3	0.4560	0.6769	0.5575	3
ES16	0.8574	2	0.4469	0.6686	0.5619	2
MP17	0.8836	1	0.5455	0.7171	0.5520	3
MP18	0.8684	2	0.5043	0.6873	0.5582	2
MP19	0.8611	3	0.4410	0.6676	0.5633	1
OT20	0.8741	3	0.4233	0.6780	0.5632	3
OT21	0.8871	2	0.4254	0.6798	0.5661	2
OT22	1.0128	1	0.2417	0.5076	0.6661	1
OV23	0.8654	4	0.5122	0.7368	0.5401	4
OV24	1.0184	2	0.2339	0.4819	0.6788	1
OV25	0.8953	3	0.3950	0.6324	0.5860	3
OV26	1.0338	1	0.2354	0.5009	0.6736	2
PP27	0.9883	5	0.2881	0.5607	0.6380	5
PP28	1.0661	2	0.2002	0.4617	0.6978	2
PP29	1.0490	4	0.2189	0.4866	0.6831	4
PP30	1.1523	1	0.1193	0.3537	0.7652	1
PP31	1.0568	3	0.2133	0.4804	0.6875	3

5.2 IF TOPSIS based risk results

Using the aggregated IFNs values (as tabulated under IF-FMEA) for the set of listed failure causes, reference series were established using Eqs. (17) and (18) for both the minimum reference series value and the maximum reference series value. The reference series for the rotor turbine RT1 under O is shown below.

Reference series for minimum value $\tilde{r}^{-}=(0,1)$ under O

$$\left\{d_{ifd_O}\left(0.4763,0.4775\right)\right\}=\frac{1}{2}\left\{\left(\left|0.4763-0\right|\right)+\left(\left|0.4775-1\right|\right)\right\}=0.7534$$

Reference series for maximum value $\tilde{r}^{+}=(1,0)$ under O

$$\left\{d_{ifd_O}\left(0.4763,0.4775\right)\right\}=\frac{1}{2}\left\{\left(\left|0.4763-1\right|\right)+\left(\left|0.4775-0\right|\right)\right\}=0.7466$$

Other reference series under S and D were calculated in the same manner. Similarly, reference series were established for other listed failure causes, of the considered unit, for both the minimum and maximum values. Using the reference values for both the minimum and maximum values in Eqs. (19) and (20), for all listed failure causes, IF-PIS and IF-NIS values were calculated taking the same value of restriction constant as that of IF-FMEA. Taking the same value of restriction constant as that of IF-FMEA in Eq. (21), the relative coefficient score for all failure causes were calculated and are shown in Table 9.

5.3 Comparative analysis results

Table 9 shows RT1, SV5, TJ7, AP11, ES14, MP17, OT22, OV26 and PP30 categorised under turbine rotor, solenoid valve, thrust and journal bearing, auxiliary oil pump, emergency stop valve, main oil pump and throttle valve, alternator rotor, oil tank and valves, and pump with their corresponding IFHWED output scores: 1.0588, 0.9030, 1.0811, 1.0439, 0.9794, 0.8836, 1.0128, 1.0338 and 1.1523 were found to be the most critical failure causes with rank first. When IF-TOPSIS approach is implemented within the proposed IF-FMEA, the failure causes found to be the most critical ones are: RT1, SV5, TJ7, AP11, ES14, MP19 OT22, OV24 and PP30. They were ranked as first with the magnitude of relative coefficient as: 0.6910, 0.5991, 0.6987, 0.6893, 0.6243, 0.5633, 0.6661 0.6788, 0.7652, respectively. It has been found that four failure causes, MP17 MP19, OV24 and OV26, were ranked differently with the IF-TOPSIS approach.

High degree of compatibility among both the approaches has been observed as majority of the failure causes were ranked similar. The similarity in ranking results prove the robustness of the proposed novel IF-FMEA approach based ranking results. The most critical component as identified with the proposed model will be useful for developing the accurate maintenance policy for the considered unit, and prove to be useful in avoiding the effect of reactive agents during the system operation and, hence, contribute to the system's operational safety.

5.4 Sensitivity analysis-based simulation results

IF-TOPSIS approach has been chosen to check the stability of the ranking derived against the relative coefficient. As the value of restriction constant, ϕ, has been selected in Eqs. (19) and (20) to find the value of IF-NIS and IF-PIS, and hence the relative coefficient, so, it becomes necessary to conduct the sensitivity analysis. Eleven simulations for each failure cause were run for ϕ =0-1 with an increment of 0.1, to check the variation in the relative coefficient values, and, hence, change in ranking of identified failure causes. When the simulation is run for a set of failure causes of turbine rotor such as RT1, RT2 and RT3, no change in ranking results have been observed with the change in the ϕ values, as shown in Table 10.

Table 10 Ranking of failure causes at different values of restriction constant, ϕ

ϕ values	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Failure causes	Ranks										
RT1	1	1	1	1	1	1	1	1	1	1	1
RT2	3	3	3	3	3	3	3	3	3	3	3
RT3	2	2	2	2	2	2	2	2	2	2	2
SV4	3	3	3	2	2	2	2	2	2	2	2
SV5	1	1	1	1	1	1	1	1	1	1	1
SV6	2	2	2	3	3	3	3	3	3	3	3
TJ7	1	1	1	1	1	1	1	1	1	1	1
TJ8	2	2	2	2	2	2	2	2	2	2	2
TJ9	4	4	4	3	3	3	3	3	3	3	3
TJ10	3	3	3	4	4	4	4	4	4	4	4
AP11	1	1	1	1	1	1	1	1	1	1	1
AP12	3	3	3	3	3	3	3	3	3	3	3
AP13	2	2	2	2	2	2	2	2	2	2	2
ES14	1	1	1	1	1	1	1	1	1	1	1
ES15	3	3	3	3	3	3	3	3	3	3	3
ES16	2	2	2	2	2	2	2	2	2	2	2
MP17	2	2	2	3	3	3	3	3	3	3	3
MP18	1	1	1	1	1	2	2	2	2	2	2
MP19	3	3	3	2	2	1	1	1	1	1	1
OT20	3	3	3	3	3	3	3	3	3	3	3
OT21	2	2	2	2	2	2	2	2	2	2	2
OT22	1	1	1	1	1	1	1	1	1	1	1
OV23	4	4	4	4	4	4	4	4	4	4	4
OV24	1	1	1	1	1	1	1	1	2	2	2
OV25	3	3	3	3	3	3	3	3	3	3	3
OV26	2	2	2	2	2	2	2	2	1	1	1
PP27	5	5	5	5	5	5	5	5	5	5	5
PP28	2	2	2	2	2	2	2	2	2	2	2
PP29	4	4	4	4	4	4	4	4	4	4	4
PP30	1	1	1	1	1	1	1	1	1	1	1
PP31	3	3	3	3	3	3	3	3	3	3	3

The first change in the rank is noted for the set of failure causes under solenoid valve, notated as SV4 and SV6, while the rank of SV5 remains unchanged for the entire simulation. The rank of SV4 changes from 3rd to 2nd when ϕ value changes from 0.2 to 0.3, and the rank of SV6 changes from 2nd to 3rd for the similar change in value of ϕ as that of SV4. Also, the change in ranking is observed for TJ9 from 4th to 3rd when the value of ϕ is changed from 0.2 to 0.3. The failure cause TJ10 change in rank is seen from 3rd to

4th for the same change of ϕ. Likewise, for the listed failure causes under other subsystems, namely thrust and journal bearing (TJ), auxiliary oil pump (AP), emergency stop valve (ES), main oil pump and throttle valve (MP), alternator rotor (OT), oil tank and valves (OV) and pumps (PP), the ranking results were analysed with the change in ϕ values represented graphically in Figs. 3-11. It has also been observed that, out of total 31 listed failure causes, only 9 failure causes show a change in ranking, while the remaining ones show similar ranking results with the change in the ϕ value. Hence, 29.03% of the failure causes illustrate change in the ranking result for the entire run of simulations, whereas 70.97% show similar rank for failure causes when simulation was run for different values of ϕ. The effect of the restriction constant value on the ranking trend of the listed failure causes under each subsystem are represented graphically in Figs. 3-11.

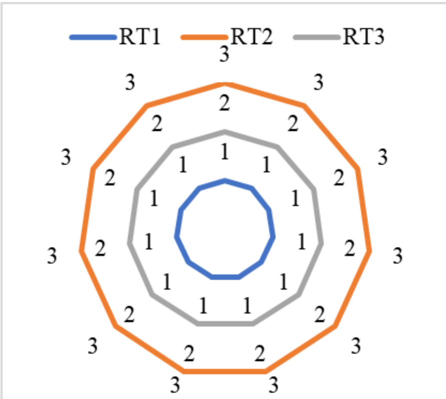

Fig. 3 Sensitivity analysis: Rotor

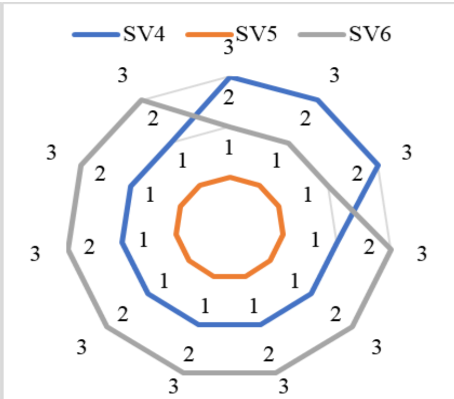

Fig. 4 Sensitivity analysis: Solenoid valve

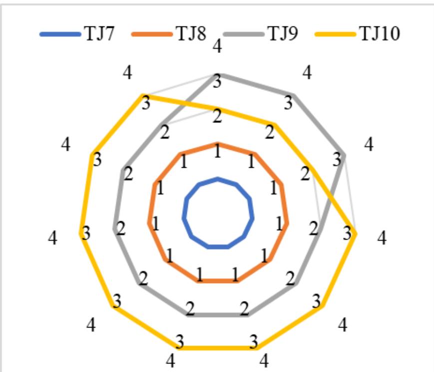

Fig. 5 Sensitivity analysis: Thrust and and journal bearing

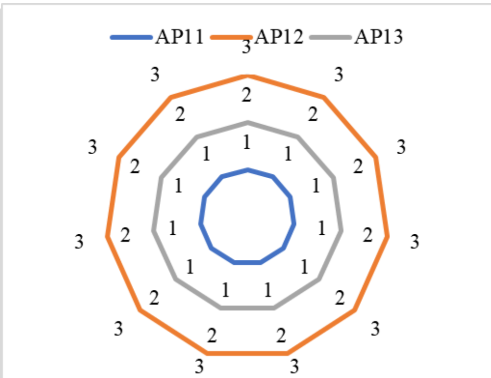

Fig. 6 Sensitivity analysis: Auxiliary oil pump

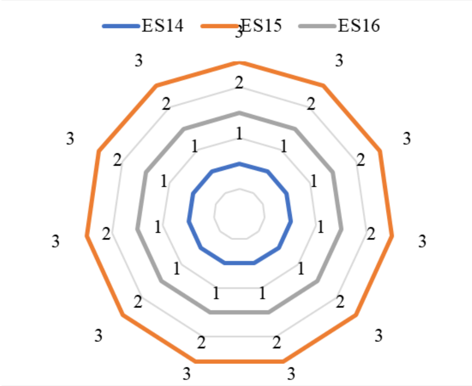

Fig. 7 Sensitivity analysis: Emergency stop valve

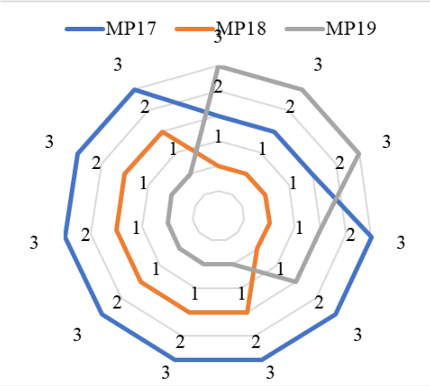

Fig. 8 Sensitivity analysis: Main oil pump

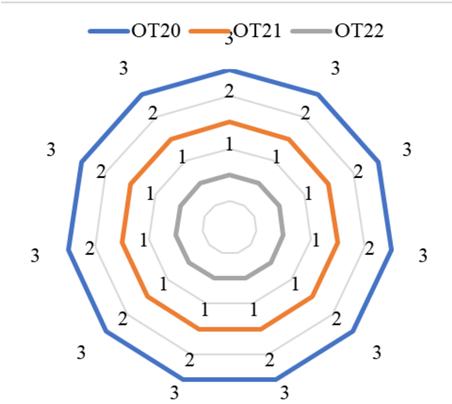

Fig. 9 Sensitivity analysis: Alternator rotor

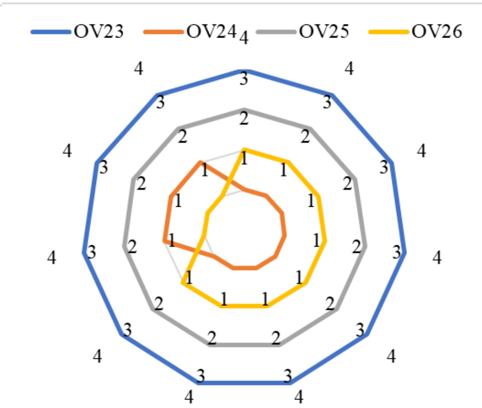

Fig. 10 Sensitivity analysis: Oil tank and valves

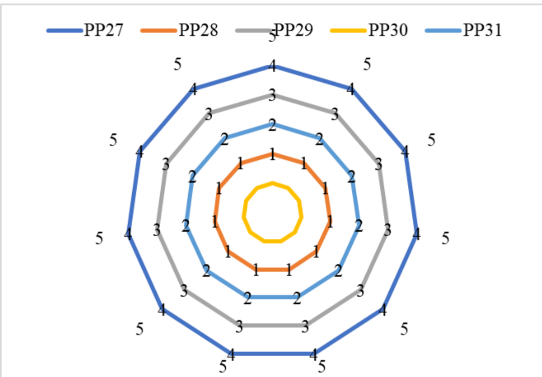

Fig. 11 Sensitivity analysis: Pump

6. CONCLUSIONS

A novel IF-FMEA approach based integrated framework was proposed to study and analyse the operational risk associated with TAU in sugar mill industry, and, therewith, to minimize or eliminate the problem of plant's unavailability and accidental hazards. The IF-FMEA approach has been applied to investigate the critical failure causes, and ranking as per the IFHWED score value was done. The proposed model overcomes the limitations of FMEA approach in an effective decision making of critical components. The IF-TOPSIS approach has also been implemented within the novel IF-FMEA approach to check the stability of the ranking results on comparative basis. From the comparative analysis, it has also been found that most of the ranking results of failure causes, as calculated, were found the same with the implementation of both the approaches, with exception of failure causes such as MP17, MP19, OV24, OV26. The highest ranked failure causes are often responsible for creating the problem of corrosion inside different parts of the TAU system. Those are responsible for sudden failure and accidental hazards. Hence, utmost remedial actions during maintenance of the unit should be implemented as per the criticality of the listed failure causes, for example, the most critical failure cause under the rotor turbine is scaling of rotor blade and thus, parameters which form scaling should be monitored closely to avoid scaling. Moreover, all the parameters which are responsible for the critical failure cause should be kept within permissible limit, and are closely monitored by operators of TAU system to avoid failure to enhance the availability of the unit. The sensitivity analysis results also show less change in ranking of failure causes with the change in ϕ values under the IF-TOPSIS approach, which indicates robustness of the proposed integrated framework methodology.

The accuracy of results of the proposed two-phase integrated framework is based on the quality of feedback collected from the experts for conducting the risk analysis. In the case that any component/subsystem is found missing during the collection of feedback from experts, the result will be affected and this is, therefore, considered to be one of the limitations of the proposed framework.

The proposed two-phase integrated framework can be implemented in other process industries or other subsystem of sugar mill industry, thermal power plants and other bio generation power plants to carry the risk analysis. The risk arises due to chemical hazards, fire explosion, threats due to poisonous fumes in chemical industries. Gas and oil refineries can also be analysed by implementing the proposed integrated framework. Moreover, different Multi Criteria Decision Making (MCDM) techniques based on IF concept could be implemented to conduct the risk analysis of industrial system. A comparison of fuzzy based approaches with those of IF based approaches is seen as scope of future work.

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