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BEHAVIOUR ANALYSIS OF COAL HANDLING SYSTEM OF A THERMAL POWER PLANT USING FUZZY METHODOLOGY

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Abstract This paper mainly focuses on the reliability analysis of a coal handling system (CHS) of a medium sized thermal power plant employing a fuzzy lambda tau approach and petrinet model. The analysis has been carried out qualitatively as well as quantitatively. In qualitative analysis, a petrinet model analogous to fault tree of CHS has been obtained. In quantitative analysis, several reliability indicators of CHS namely failure rate, repair time, availability, reliability, mean time between failure and expected number of failures have been evaluated using fuzzy lambda tau approach with trapezoidal fuzzy numbers at various spread levels $\pm 15\%$, $\pm 25\%$ and $\pm 40\%$ to address the uncertainty and impreciseness in data. The use of trapezoidal fuzzy numbers presents more realistic and flexible behaviour analysis of coal handling system. The results are of great importance to the system analyst to improve the system performance of coal handling system by implementing appropriate maintenance policies.

1 Introduction

In India, more than 65 percent of the required power is supplied by thermal power plants and coal is currently the most common fuel used in these plants. One of the most critical requirements of any power plant is to ensure that it is available at all times in order to ensure uninterrupted power supply. To enhance the availability of a complicated power plant, each of its subsystems must be sufficiently reliable and maintainable. Although failures are unavoidable in these subsystems and their components, but they can be avoided by framing and implementing an appropriate maintenance policy. Therefore, in order to ensure high availability of a thermal power plant, it is required to analyse behaviour of its subsystems.

A large number of researchers have worked in the field of behaviour analysis to increase the availability of various real-world industrial systems. Kumar et al. [1] applied the supplemental variable technique to examine the operational behaviour of the paper industry's bleaching and screening systems. Arora and Kumar [2] focused at mean time between failure and availability and employed Markov birth-death technique to examine the availability of steam and power generation systems of a thermal power plant.

Arora and Kumar [3] further employed Markov technique for stochastic behaviour evaluation and maintenance scheme of ash handling system of a thermal power plant. The use of Markov technique in measuring the performance of various industrial systems necessitates a huge amount of data, that is difficult to collect due to some constraints like operator error, budget restrictions and determining unusual events such as equipment failure among others. Thus, fuzzy methodology has been adopted by several academicians in various fields to work with uncertain, imprecise and vague data.

In fuzzy methodology, the choice of membership function is very important. There is a variety of membership functions available to represent fuzzy numbers such as normal, trapezoidal, triangular, gamma etc. But, most of the researchers employed triangular fuzzy numbers in fuzzy methodology for reliability analysis due to their simplicity. Knezevic and Odoom [4] employed triangular fuzzy numbers in fuzzy lambda tau technique for computation of numerous reliability indicators to study the reliability of repairable systems. Sharma et al. [5, 6] used triangular fuzzy numbers in fuzzy methodology for predicting the behaviour of a paper mill's forming unit. Sharma and Sharma [7] estimated the reliability, availability and maintainability of a paper mill utilizing triangular fuzzy numbers in fuzzy methodology based integrated framework. Kumar and Panchal [8] implemented fuzzy methodology with triangular fuzzy numbers for reliability studies of compressor house unit in a thermal power plant. Panchal and Kumar [9] investigated the unpredictable behaviour of power generating unit of thermal power plant. Panchal and Kumar [10] implemented fuzzy methodology with triangular fuzzy numbers to analyse stochastic behaviour of coal handling system in a thermal power plant.

Princy and Dhenakaran [11] presented a comparison study of triangular and trapezoidal membership functions. They concluded that inspite of the fact that the use of trapezoidal membership function makes the process quite complex, even then, their performance is better than triangular membership function. The use of trapezoidal fuzzy number demonstrates more flexible analysis. To the best of authors' knowledge, almost no work has been found in the literature on using trapezoidal fuzzy numbers with fuzzy methodology to analyse behaviour of repairable systems. Therefore, in view of observations made by Princy and Dhenakaran [11], this paper presents the behaviour analysis of coal handling system of a thermal power plant using fuzzy lambda tau approach with trapezoidal fuzzy numbers taking various spreads levels $\pm 15\%$, $\pm 25\%$ and $\pm 40\%$.

2 Proposed Methodology

The methodology for reliability analysis of repairable system adopted in this paper comprises of steps given in figure 1.

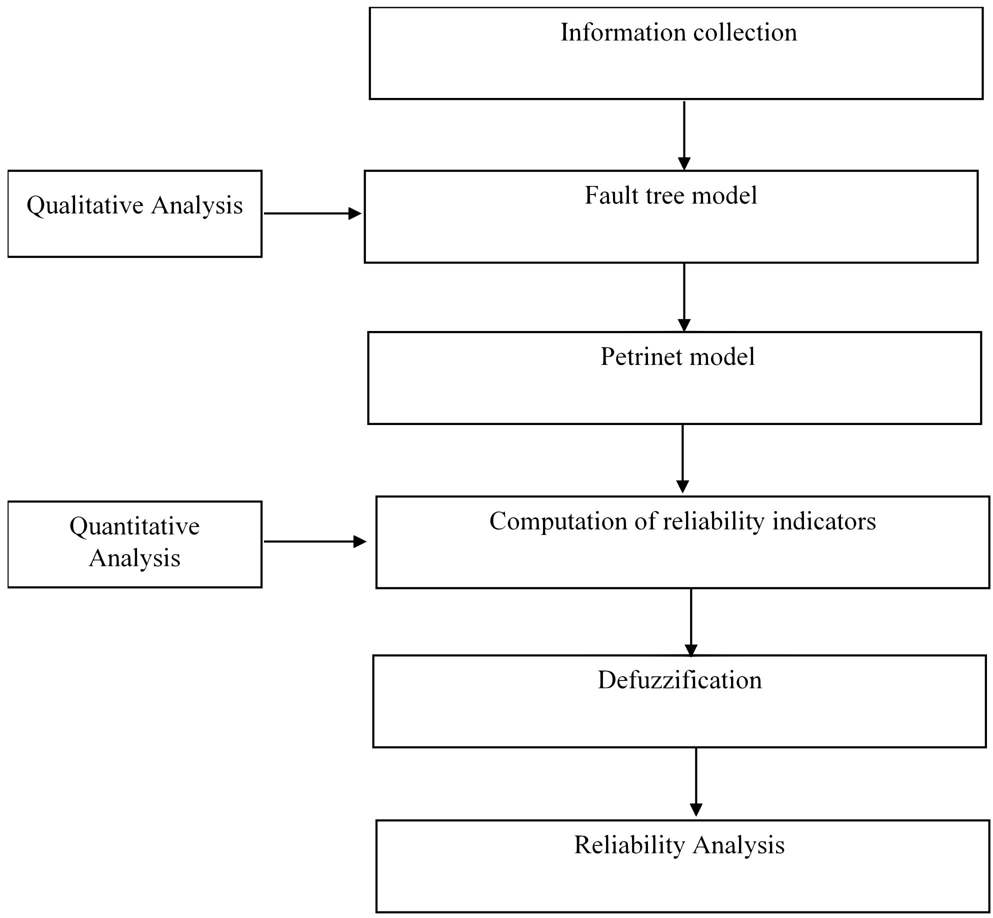

Figure 1. Procedural steps of proposed methodology

3 Failure Analysis Approach

Fault tree analysis and petrinet are reliability tools which represent the parallel/series arrangements of numerous subsystems of a system with the help of AND/OR indicators, respectively. Petrinet is chosen over fault tree analysis as it is easier to obtain minimal cut and path sets using petrinet [12]-[16]. Figure 2 shows a fault tree AND model, OR model and their corresponding petrinet models.

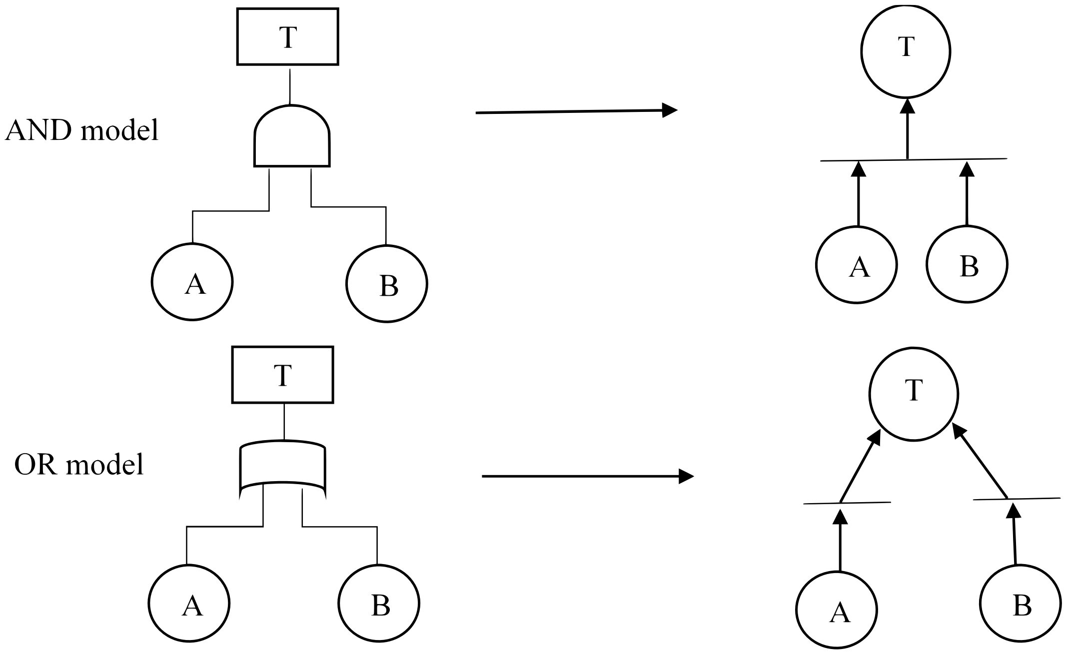

Figure 2. Fault tree models and corresponding petrinet models

4 Basic Concepts of Fuzzy Sets

The basic concepts of fuzzy set theory [17]-[22], used in this paper are given as follows:

4.1 Fuzzy set

A fuzzy set $\tilde{A}$ defined on universal set X is defined by

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) \colon x \in X\}, \tag{4.1}$$

where, $\mu_{\tilde{A}}(x)$ is the membership function which associates each element x in X, a real number in the interval [0,1].

4.2 Trapezoidal fuzzy number

A fuzzy number $\tilde{A} = (a_1, a_2, a_3, a_4)$ is said to be trapezoidal fuzzy number if its membership function $\mu_{\tilde{A}}(x)$ is given by

$$\mu_{\tilde{A}}(x) = \begin{cases} \frac{x-a_1}{a_2-a_1}, & a_1 \leq x \leq a_2 \\ 1, & a_2 \leq x \leq a_3 \\ \frac{a_4-x}{a_4-a_3}, & a_3 \leq x \leq a_4 \\ 0, & \text{otherwise.} \end{cases} \tag{4.2}$$

The α-cut of the fuzzy number$\tilde{A}$, which is denoted by

$$[a_1^\alpha, a_4^\alpha] = [(a_2 - a_1)\alpha + a_1, (a_3 - a_4)\alpha + a_4],$$

where, $\alpha \in [0, 1]$ is shown in the figure 3.

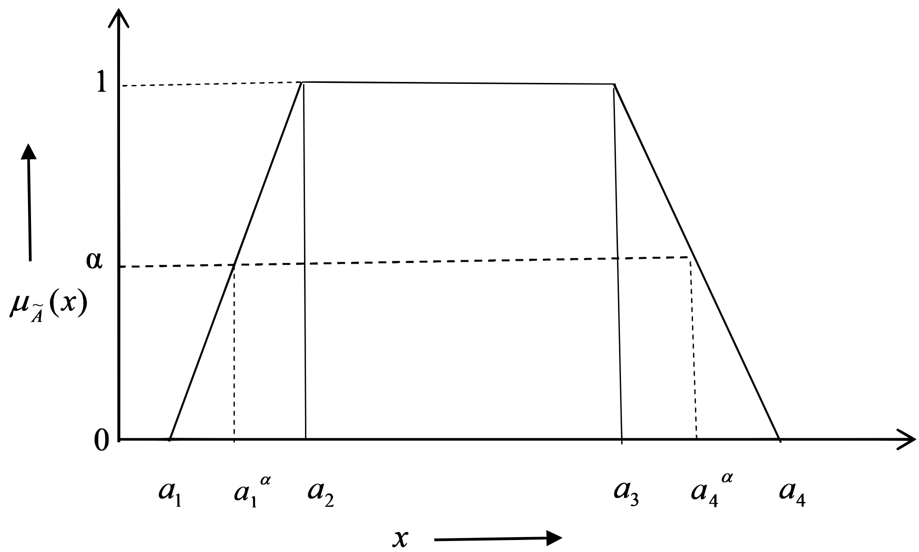

Figure 3. Trapezoidal fuzzy number with α-cut

5 Case Study

In this paper, CHS of a thermal power plant in northern India with a capacity of 1360.8 MW has been considered. The raw material coal is transferred from coal mines through railway wagons in this thermal power plant. In CHS, the transferred coal is emptied using wagon tipplers before being transferred to the crusher unit via conveyor belts. The coal passes via powerful magnets while running over conveyors, which remove any iron bits. Large stones are manually removed by unskilled workers. After that, the coal is delivered to the crusher assembly. Many enormous swinging hammers joined to the rotor periphery crush the coal. Depending on the plant's requirements, the crushed coal is either delivered to pulveriser mills or stored in custody. Figure 4 depicts the CHS's schematic diagram. The CHS is made up of following three subsystems:

i. Coal Unloading Subsystem [SS_1]: It is made up of a series of side-arm chargers and wagon tipplers so that if one fails, the entire subsystem will fail.

ii. Conveyor Belt Subsystem [SS_2]: A three-belt system is used to transport coal that is connected in series and a Programmable Logic Controller controls these conveyor belts. There are two units on each belt (One is currently in use, while the other is on standby). If the standby belts also fail, the system will be completely stopped.

iii. Crusher House Subsystem [SS_3]: Vibrating screen, shute and crushers (two bearings arranged in series) are connected in a series in this unit. The coal is crushed to a size of 35mm or less in the crusher. Its failure might bring the entire system to a halt.

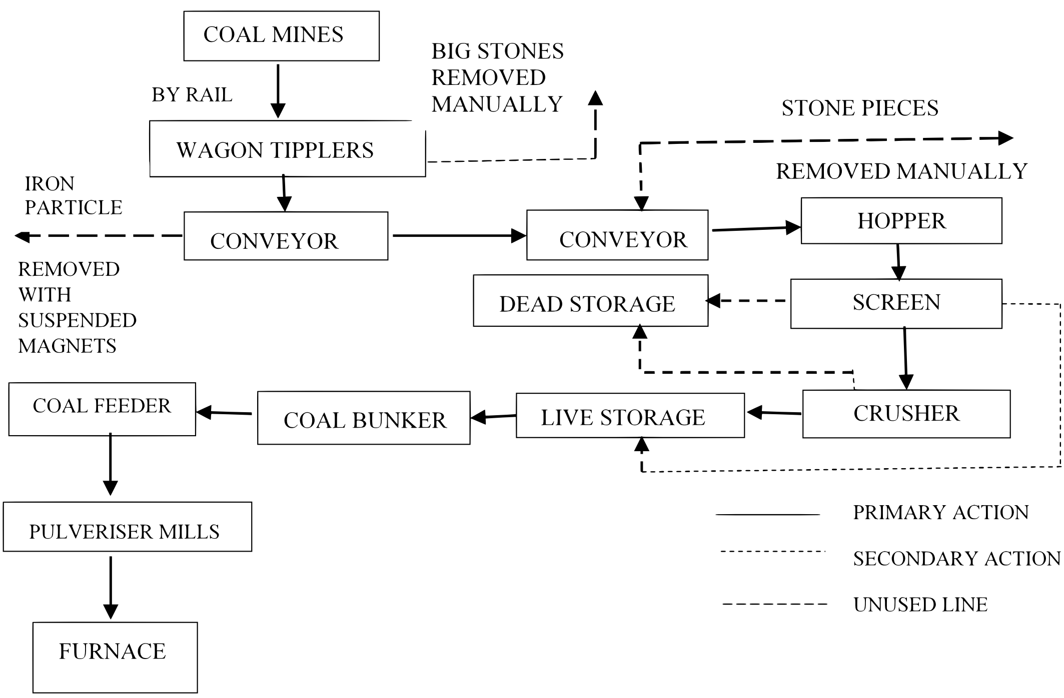

Figure 4. Schematic flow diagram of coal handling system

6 Reliability Analysis of Coal Handling System

Step 1. Information collection: The repair and failure data for each subsystem component are taken from the CHS maintenance log book which were checked by maintenance expert and are presented in table 1.

Table 1. Repair and failure data for CHS

Components	Repair time τ_k (h)	Failure rate λ_k (failures/h)
Side arm charger (k=1)	3	1.2×10^{-4}
Wagon tippler (k=2)	3	1.2×10^{-4}
Belt conveyor (k=3,4,5,6,7,8)	15	1.4×10^{-5}
Shute (k=9)	3	1.2×10^{-4}
Vibrating screen (k=10)	3	1.2×10^{-4}
Crushing bearing (k=11,12)	10	2.3×10^{-4}

Step 2. Construction of fault tree model and petrinet model: In qualitative analysis, first fault tree model of CHS (Fig. 5) is constructed and then its petrinet model (Fig. 6) is constructed. In these models, the OR gate depicts the component's series arrangement, whereas the AND gate depicts the component's parallel arrangement.

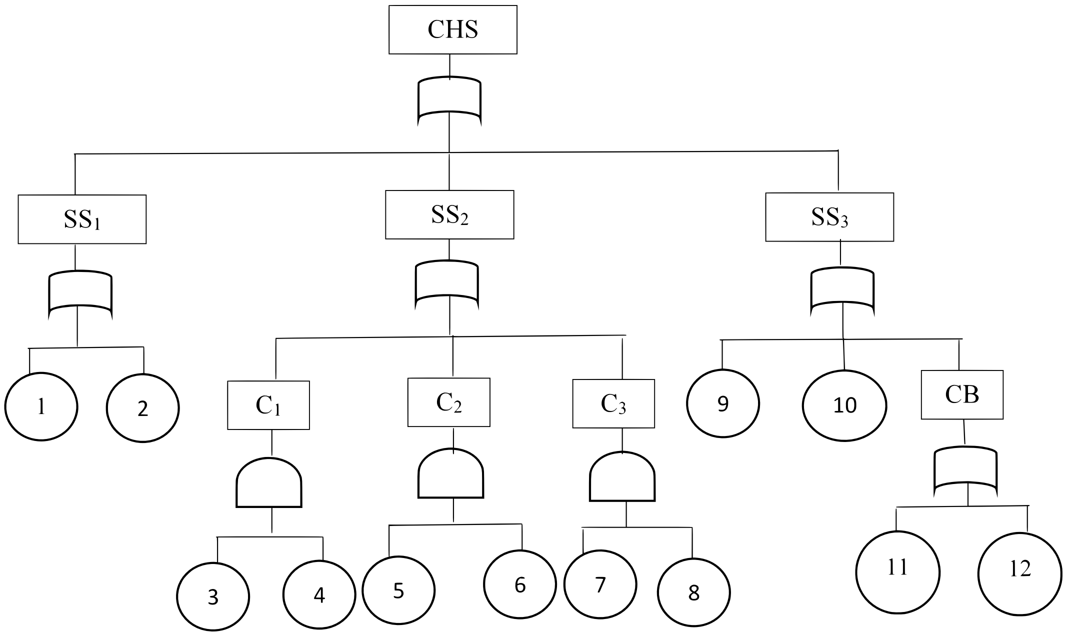

Figure 5. Fault tree model of CHS

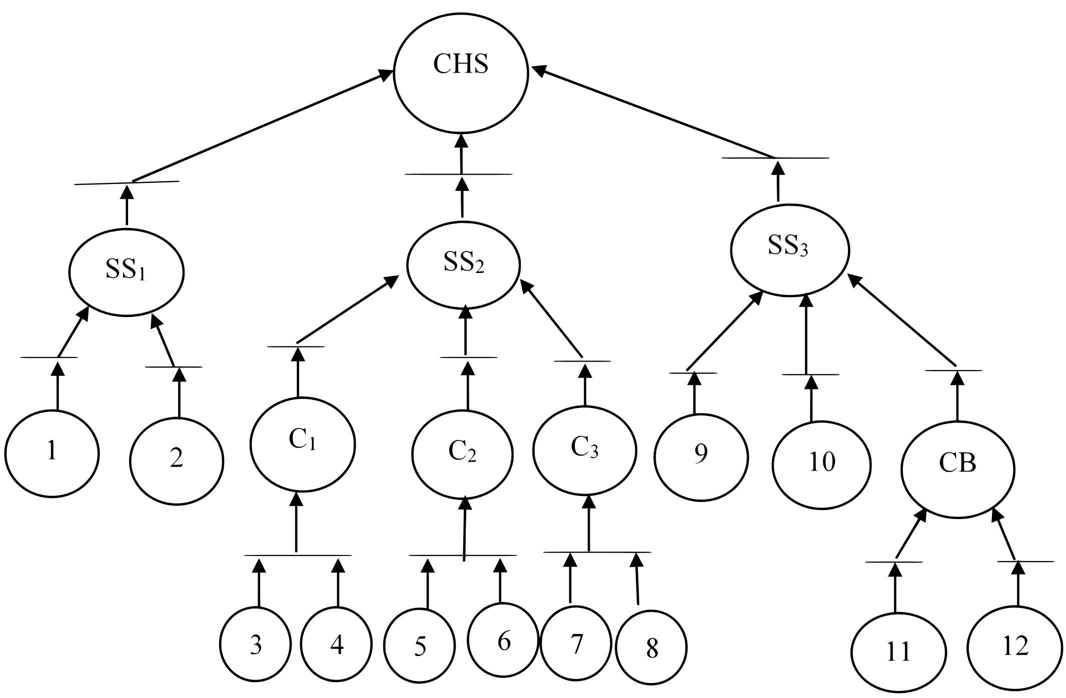

Figure 6. Petrinet model of CHS

Step 3. Computation of fuzzy reliability indicators: In quantitative analysis, the imprecise and vague failure/repair data obtained from various sources is converted into the trapezoidal fuzzy numbers using trapezoidal membership function with various spreads. For instance, figure 7 depicts the trapezoidal fuzzy number at $\pm 15\%$ spread on crisp input data for repair time (τ_1) and failure rate (λ_1) of the first component i.e. side arm charger.

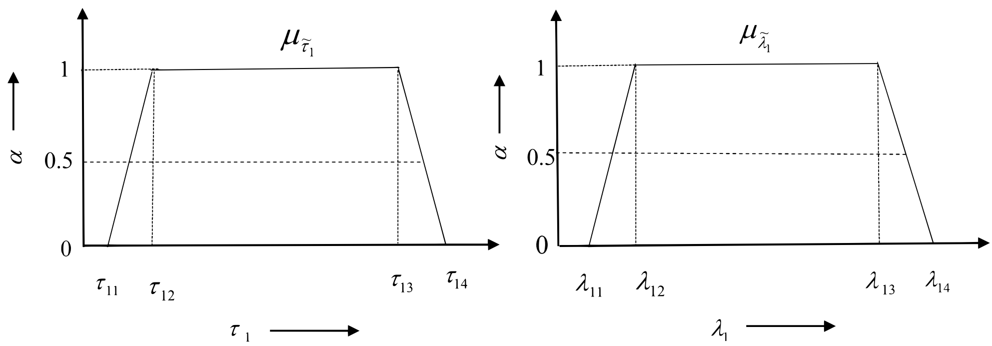

Figure 7. Trapezoidal fuzzy number for τ_1 and λ_1 at $\pm 15\%$ spread of side arm charger

Further, using extension principle along with $\alpha-$cut and interval arithmetic operations on basic lambda tau expressions given in table 2 for OR/AND gates, the fuzzy transition expressions for repair time (τ) and failure rate (λ) for OR/AND gates of the petrinet model are obtained. Equations (6.1−6.4) present the interval expressions for fuzzy numbers with trapezoidal membership functions for OR/AND gate transition. Using equations (6.1−6.4), the repair time and failure rate for the top most position of petrinet model of CHS have been calculated.

Table 2. Basic lambda tau expressions for OR/AND gate

Gate	λ_{OR}	τ_{OR}	λ_{AND}	τ_{AND}
Expressions ($n-$**inputs**)	$\sum_{k=1}^{n} \lambda_k$	$\frac{\sum_{k=1}^{n} \lambda_k \tau_k}{\sum_{k=1}^{n} \lambda_k}$	$\prod_{l=1}^{n} \lambda_l [\sum_{k=1}^{n} \prod_{l=1,k\neq l}^{n} \tau_l]$	$\frac{\prod_{k=1}^{n} \tau_k}{\sum_{l=1}^{n} [\prod_{k=1,k\neq l}^{n} \tau_k]}$

Interval expressions for OR gate transition

$$\tau^{\alpha} = \left[\frac{\sum_{k=1}^{n} [\{\lambda_{k2} - \lambda_{k1})\alpha + \lambda_{k1}\} \cdot \{\tau_{k2} - \tau_{k1})\alpha + \tau_{k1}\}]}{\sum_{k=1}^{n} \{(\lambda_{k3} - \lambda_{k4})\alpha + \lambda_{k4}\}}, \right.$$
$$\left. \frac{\sum_{k=1}^{n} [\{(\lambda_{k3} - \lambda_{k4})\alpha + \lambda_{k4}\} \cdot \{(\tau_{k3} - \tau_{k4})\alpha + \tau_{k4}\}]}{\sum_{k=1}^{n} \{(\lambda_{k2} - \lambda_{k1})\alpha + \lambda_{k1}\}} \right], \quad (6.1)$$

$$\lambda^{\alpha} = \left[\sum_{k=1}^{n} \{(\lambda_{k2} - \lambda_{k1})\alpha + \lambda_{k1}\}, \sum_{k=1}^{n} \{(\lambda_{k3} - \lambda_{k4})\alpha + \lambda_{k4}\} \right]. \quad (6.2)$$

Interval expressions for AND gate transition

$$\tau^{\alpha} = \left[\frac{\prod_{k=1}^{n} \{\tau_{k2} - \tau_{k1})\alpha + \tau_{k1}\}}{\sum_{l=1}^{n} [\prod_{k=1,k\neq l}^{n} \{\tau_{k3} - \tau_{k4})\alpha + \tau_{k4}\}]}, \frac{\prod_{k=1}^{n} \{\tau_{k3} - \tau_{k4})\alpha + \tau_{k4}\}}{\sum_{l=1}^{n} [\prod_{k=1,k\neq l}^{n} \{\tau_{k2} - \tau_{k1})\alpha + \tau_{k1}\}]} \right], \quad (6.3)$$

$$\lambda^{\alpha} = \left[\prod_{k=1}^{n} \{(\lambda_{k2} - \lambda_{k1})\alpha + \lambda_{k1}\} \cdot \sum_{l=1}^{n} [\prod_{k=1,k\neq l}^{n} \{\tau_{k2} - \tau_{k1})\alpha + \tau_{k1}\}], \right.$$
$$\left. \prod_{k=1}^{n} \{(\lambda_{k3} - \lambda_{k4})\alpha + \lambda_{k4}\} \cdot \sum_{l=1}^{n} [\prod_{k=1,k\neq l}^{n} \{\tau_{k3} - \tau_{k4})\alpha + \tau_{k4}\}] \right]. \quad (6.4)$$

Further, various reliability indicators namely, failure rate, repair time, availability, reliability, mean time between failure (MTBF) and expected number of failures (ENOF) are evaluated using expressions in table 3 for different degrees of membership α = 0.0 (0.1) 1.0 at different spread levels $\pm 15\%$, $\pm 25\%$ and $\pm 40\%$.

Table 3. Expressions for reliability indicators

Reliability Indicator	**Expression**
Mean time to repair	$MTTR = \frac{1}{\gamma} = \tau$
Mean time to failure	$MTTF = \frac{1}{\lambda}$
Availability	$A = \frac{\gamma}{\gamma+\lambda} + \frac{\lambda}{\gamma+\lambda} e^{-(\gamma+\lambda)t}$
Reliability	$R = e^{-\lambda t}$
Mean time between failure	$MTBF = MTTF + MTTR$
Expected number of failures	$ENOF = \frac{\lambda\gamma t}{\gamma+\lambda} + \frac{\lambda^2}{(\gamma+\lambda)^2}[1 - e^{-(\gamma+\lambda)t}]$

Table 4 and table 5 present the right and left side spread fuzzy values, respectively, of various reliability indicators of coal handling system at $\pm 15\%$ spread for different degrees of membership α = 0.0 (0.1) 1.0. Further, the trends of fuzzy values of various reliability indicators at $\pm 15\%$, $\pm 25\%$ and $\pm 40\%$ spreads are shown in figure 8.

Table 4. The right side spread values of reliability indicators of CHS at 15% spread

α	Failure rate (/h)	Repair time (h)	Availability	Reliability	MTBF (h)	ENOF
1	0.001034	12.345763	0.997186	0.867508	1194.360893	0.171685
0.9	0.001039	12.757454	0.997293	0.868194	1201.376221	0.172394
0.8	0.001043	13.183219	0.997395	0.868879	1208.479819	0.173101
0.7	0.001048	13.623570	0.997494	0.869566	1215.673459	0.173804
0.6	0.001053	14.079044	0.997590	0.870253	1222.958962	0.174504
0.5	0.001058	14.550197	0.997681	0.870940	1230.338200	0.175202
0.4	0.001062	15.037610	0.997770	0.871628	1237.813100	0.175895
0.3	0.001067	15.541884	0.997855	0.872317	1245.385642	0.176586
0.2	0.001072	16.063649	0.997938	0.873006	1253.057861	0.177273
0.1	0.001076	16.603559	0.998017	0.873695	1260.831855	0.177956
0	0.001081	17.162293	0.998093	0.874386	1268.709780	0.178636

Table 5. The left side spread values of reliability indicators of CHS at 15% spread

α	Failure rate (/h)	Repair time (h)	Availability	Reliability	MTBF (h)	ENOF
1.0	0.000846	3.335157	0.987395	0.840536	970.431186	0.141738
0.9	0.000841	3.226624	0.986922	0.839872	965.946454	0.140965
0.8	0.000837	3.121499	0.986431	0.839209	961.504553	0.140192
0.7	0.000832	3.019673	0.985922	0.838547	957.104847	0.139417
0.6	0.000827	2.921043	0.985394	0.837885	952.746708	0.138642
0.5	0.000823	2.825508	0.984846	0.837223	948.429527	0.137867
0.4	0.000818	2.732970	0.984278	0.836563	944.152701	0.137091
0.3	0.000813	2.643335	0.983689	0.835902	939.915643	0.136314
0.2	0.000808	2.556513	0.983077	0.835242	935.717778	0.135537
0.1	0.000804	2.472414	0.982444	0.834583	931.558541	0.134760
0	0.000799	2.390954	0.981786	0.833924	927.437377	0.133982

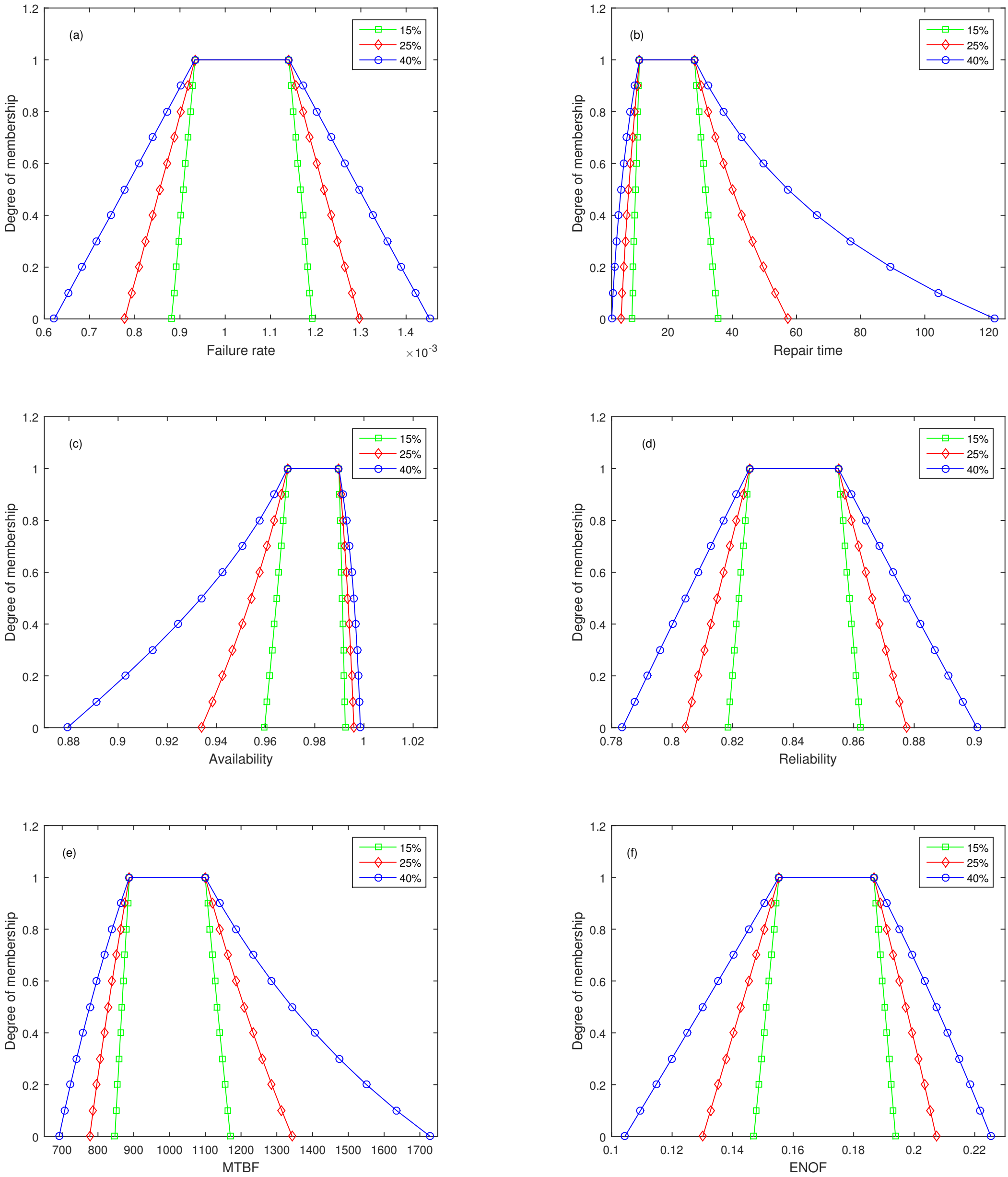

Figure 8. Fuzzy values of reliability indicators (a) Failure rate, (b) Repair time, (c) Availability, (d) Reliability, (e) MTBF and (f) ENOF at ±15%, ±25% and ±40% of the CHS

Step 4. Defuzzification of fuzzy reliability indicators: Defuzzification is the process by which fuzzy output is converted into crisp output. In order to make maintenance judgements with maintenance activities, center of area method has been employed to obtain the defuzzified values at ±15%, ±25% and ±40% spreads of reliability indicators using equation (6.5). The crisp and defuzzified values of reliability indicators at ±15%, ±25% and ±40% spreads are presented in table 6.

$$\bar{v} = \frac{\int_{v_1}^{v_2} v \cdot \mu_{\tilde{A}}(v)dv}{\int_{v_1}^{v_2} \mu_{\tilde{A}}(v)dv} \tag{6.5}$$

Table 6. Defuzzified and crisp values of reliability indicators

Reliability Indicator	**Crisp Value**			**Defuzzified Values**
		Spreads		
		±15%	±25%	±40%
Failure rate (/h)	9.400100×10^{-4}	9.400000×10^{-4}	9.400000×10^{-4}	9.400280×10^{-4}
Repair time (h)	6.425553	8.886708	13.535049	34.491446
Availability	0.993996	0.991017	0.985353	0.965884
Reliability	0.853916	0.854104	0.854346	0.854980
MTBF (h)	1.070235×10^3	1.092427×10^3	1.123383×10^3	1.225781×10^3
ENOF	0.157011	0.156497	0.155645	0.153213

7 Results and Discussion

Figure 8 depicts the fluctuations of various reliability indicators and it is demonstrated that the membership curves of these indicators are distorted trapeziums since the use of fuzzy mathematics converts left and right linear sides of trapeziums to parabolic sides [23]. Further, table 6 presents the crisp and defuzzified values of reliability indicators at ±15%, ±25% and ±40% spreads to depict the system's behaviour. It is observed that, as the spread changes, the defuzzified values of reliability indicators also change. The failure rate does not change when the spread is increased from ±15% to ±25%, but it increases marginally when the spread is further extended from ±25% to ±40%. When the spread extends from ±15% to ±25%, repair time increases by 52.31%, availability decreases by 0.57%, reliability increases marginally, MTBF increases by 2.83% and ENOF decreases by 0.54%. When spread further increases from ±25% to ±40%, repair time increases by 154.83%, availability decreases by 1.98%, reliability increases marginally, MTBF increases by 9.12% and ENOF decreases by 1.56%. It is revealed that the repair time fluctuates most significantly in comparison to other reliability indicators, leading to a loss in system availability and thereby affecting the intended objective of maximum profit. As a result of these findings and observations, the maintenance analyst will select defuzzified values that will allow for optimal productivity and efficiency.

8 Conclusion

In order to achieve long-run availability of a repairable system, it is necessary to analyse its behaviour. The main objective of this paper is to provide a systematic framework that would enable maintenance engineers, managers and practitioners to analyse and predict system behaviour of CHS in a thermal power plant. This paper presents both qualitative and quantitative analyses of CHS. In qualitative analysis, a petrinet model analogous to fault tree of CHS has been obtained. In quantitative analysis, several reliability indicators of CHS namely failure rate, repair time, availability, reliability, MTBF and ENOF have been evaluated using fuzzy lambda tau approach with trapezoidal fuzzy numbers at various spread levels. The use of trapezoidal fuzzy numbers presents more realistic and flexible behaviour analysis of coal handling system. From the results, it is observed that the repair time varies most significantly compared to other reliability indicators, resulting in a loss in system availability, which is undesirable and hence it should be prioritized. Thus, the analysis is of great importance to the system analyst to improve the system performance of coal handling system by implementing appropriate maintenance policies.

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