BEHAVIOR ANALYSIS OF WASHING UNIT IN A PAPER PLANT EMPLOYING FUZZY APPROACH

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Abstract

Aim. *The purpose of this research is to employ a fuzzy approach to assess the system behavior of the washing unit in a paper plant using vague, uncertain and inaccurate data. The washing unit is the main operational part of a paper plant for which analysis of system behavior is important to choose an appropriate maintenance strategy. The analysis has been carried out for washing unit of a paper plant situated in northern India.* ***Methods****. The proposed approach comprises qualitative and quantitative analysis. In qualitative analysis, the basic arrangement of the washing unit is modelled by Petri Net model. In quantitative analysis, the fuzzy λ-τ approach has been used for analyzing the systems' failure behavior more accurately. Uncertainties in failure/repair data of every subsystem/component of the washing unit are quantified using trapezoidal fuzzy numbers.* ***Results.*** *To assess the performance and failure dynamic behavior of the washing unit quantitatively, six reliability parameters including failure rate, repair time, mean time between failure, expected number of failures, reliability and availability at three different spread levels have been evaluated employing trapezoidal fuzzy numbers. The fuzzified values of these reliability parameters of washing unit have been defuzzified employing center of area defuzzification technique. Further, crisp values and defuzzified values of these parameters using triangular fuzzy numbers have also been obtained. The results obtained by the proposed methodology have been compared with those obtained by fuzzy λ-τ approach based on triangular fuzzy numbers. The information/results obtained through the fuzzy λ-τ approach with trapezoidal fuzzy number are conservative in nature, therefore, these results may be used by system specialist/system analysts for the future plan of implementation.* ***Conclusion.*** *Using this approach, six reliability parameters are evaluated and the trend (increase or decrease) of these reliability parameters is examined for performance analysis of washing unit in a paper plant. Based on these investigations, suitable maintenance policy can be established that will assist maintenance manager/system analysts/engineers in improving system performance by implementing appropriate preventive maintenance procedures. As a result, it will help in achieving a long time system availability and maximizing overall productivity of the paper plant. The implications of this fuzzy reliability approach to industry maintenance and operation planning are quite beneficial.*

Keywords: paper plant, uncertain data, petri net, fuzzy methodology, reliability, trapezoidal fuzzy number

1. Introduction

Reliability analysis plays a vital role in successful functioning of a repairable industrial system. Most of the repairable industrial systems consist of various subsystems. Every subsystem is comprised of several sophisticated components. It is almost impossible to completely avoid the failure in an industrial system but it can be reduced by implementing appropriate maintenance policies. System availability is also identified as an important factor of performance for such systems. To achieve the objective of improving the availability/reliability with low-cost inputs, it is required that every component or subsystem must operate adequately and provide excellent performance. The behavior of a system under specified operating conditions can be used to design its components to minimize the failure and to plan the preventive or scheduled maintenance of the system. However, today, the behavior analysis of repairable industrial system has become a great challenge for an expert/system analyst due to technological advancements and growing complexities of components/subsystems of the system.

A number of researchers evaluated the performance of numerous operational structures in different process plants, namely thermal power plant, sugar industry, paper plant, chemical industry and urea plant. The probability of survival of an industrial system depends upon all of its basic components. Thus, the behavior of these components will assist in the analysis of its overall performance. The behavior and performance of such systems are often assessed using reliability, system availability and other reliability parameters. Many different techniques such as the Markovian approach, reliability block diagrams (RBDs), fault tree analysis (FTA), Petri Nets (PNs) and others are widely used for reliability analysis of repairable industrial systems [1-8]. However, nowadays, among these techniques, FTA and PN [5-10] are being preferred by the researchers to analyze the failure of repairable systems.

To deal with the uncertainties in data, Knezevic and Odoom [11] developed the λ-τ approach by using the fuzzy theory and the PN model. In their methodology, triangular fuzzy numbers (TFNs) have been employed to address the vagueness in the failure/repair information. Sharma et al. [12] used fuzzy λ-τ approach for behavior analysis of a large industrial system employing FTA and PNs. Sharma et al. [13] applied FTA and the fuzzy λ-τ approach to examine the reliability of complex robotic unit. Sharma et al. [14] analyzed the system behavior and performance for two grinding machines employing fuzzy λ-τ approach with PN. Garg et al. [15] analyzed the system reliability parameters of screening unit of a paper plant using a fuzzy approach. Verma et al. [16] examined the vague reliability of the combustion unit employing vague λ-τ approach with PN. Panchal et al. [17] employed a fuzzy approach for RAM and risk analysis of a chemical industry.

To fuzzify clinical information/data, Princy and Dhenakaran [18] compared trapezoidal fuzzy number (TrFN) and TFN and discovered that the classification performance of TrFN is better than that of TFN. Most recently, Sharma and Sushma [19, 20] used TrFNs to estimate the performance and behavior of coal handling unit and water circulation unit, respectively, in a thermal power plant employing fuzzy approach. Further, Sharma and Mamta [21] performed reliability analysis of the feeding system of a paper plant under fuzzy environment employing TrFN.

The major purpose of this study is to quantify the uncertainties of failure/repair data of washing unit of a paper plant using TrFN for analyzing the systems' behavior more accurately. The fuzzy λ-τ approach for behavior analysis is used together with PN modelling. Further, the obtained results from the fuzzy λ-τ approach with TrFN are compared with the results obtained using TFN. The acquired information will assist the managers in planning preventive or scheduled maintenance policies, to attain maximum system availability.

The structure of remaining part of this paper is as follows. Some important concepts of fuzzy set theory relevant to this study have been presented in section 2. The proposed methodology has been described in Section 3. Section 4 deals with the implementation of proposed methodology to perform fuzzy reliability analysis of considered unit. Lastly, section 5 presents the conclusions drawn.

2. Fuzzy Set Theory

The important concepts of fuzzy set theory used in the present study are given as [22]:

2.1. Fuzzy Set

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

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) : x \in X\} \ , \tag{1}$$

where, $\mu_{\tilde{A}}(x) \in [0,1]$ denotes the degree of membership for element x.

2.2. Fuzzy Number

A fuzzy number is a convex, normal fuzzy set defined on real line with bounded support.

2.3. Trapezoidal Fuzzy Number

A TrFN $\tilde{A}$ is a fuzzy number described as (t_1, t_2, t_3, t_4) with membership function as

$$\mu_{\tilde{A}}(x) = \begin{cases} \frac{(x-t_1)}{(t_2-t_1)}, & t_1 \le x \le t_2 \\ 1, & t_2 \le x \le t_3 \\ \frac{(t_4-x)}{(t_4-t_3)}, & t_3 \le x \le t_4 \\ 0, & \text{otherwise} \end{cases} . \tag{2}$$

The α-cut of TrFN $\tilde{A}$ given by

$$\tilde{A}^{\alpha} = [t_1^{\alpha}, \ t_4^{\alpha}] = [t_1 + (t_2 - t_1)\alpha \, , t_4 - (t_4 - t_3)\alpha] \, , \quad \alpha \in [0,1] \ , \tag{3}$$

is represented in Figure 1.

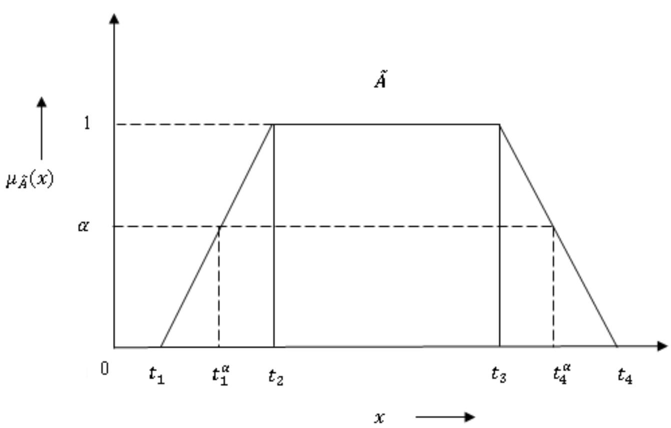

Figure 1: *α-cut for TrFN $\tilde{A}$*

3. Proposed Methodology

The behavior of a repairable system in an ambiguous environment can be analyzed using fuzzy λ-τ approach [11]. This approach uses failure and repair data of subsystems and components of considered system. This approach handles the ambiguity and vagueness in failure and repair data and hence is preferred over other approaches. The stepwise procedure of proposed methodology is as follows:

Step 1: Collection of information of various subsystems and components of washing unit.

Step 2: Construction of PN model.

Step 3: Collection of input data related to failure and repair of various subsystems and components.

Step 4: Employing TrFN for fuzzification of input data collected in step 3.

Step 5: Calculation of various reliability parameters of washing unit at different spread levels using fuzzy λ-τ approach.

Step 6: Defuzzification of fuzzified reliability parameters.

Step 7: Behavior analysis of washing unit.

4. System Description

There are several working units serving different purposes in a paper plant. In this paper, one of the main functional unit i.e. the washing unit of a paper plant situated in northern India has been studied. Washing unit of the paper plant washes the wood pulp coming out of the pulping unit with water to remove any chemicals or black liquor and prepares the fine fiber from the pulp. The schematic diagram of washing unit [23] is depicted in Figure 2.

The washing unit consists of four main subsystems, which are as follows:

- **Filter [S_1]**: This subsystem has a single filter unit, which extracts black liquor from prepared wood pulp.
- **Cleaner [S_2]**: This subsystem consists of three components, connected in parallel arrangement. These components are utilized for cleaning the pulp using centrifugal motion. Failure of one component reduces system efficiency and paper quality.
- **Screener [S_3]**: This subsystem consists of two components, which are connected in series. The wood pulp is strained by these components to separate large, unprepared and irregular fibers from it. The failure of any one component will result in the unit failure completely.

Decker [S_4]: This subsystem consists two components connected in parallel arrangement. These components remove the chemicals/darkness from prepared wood pulp. The failure of both components will result in the poor quality of paper.

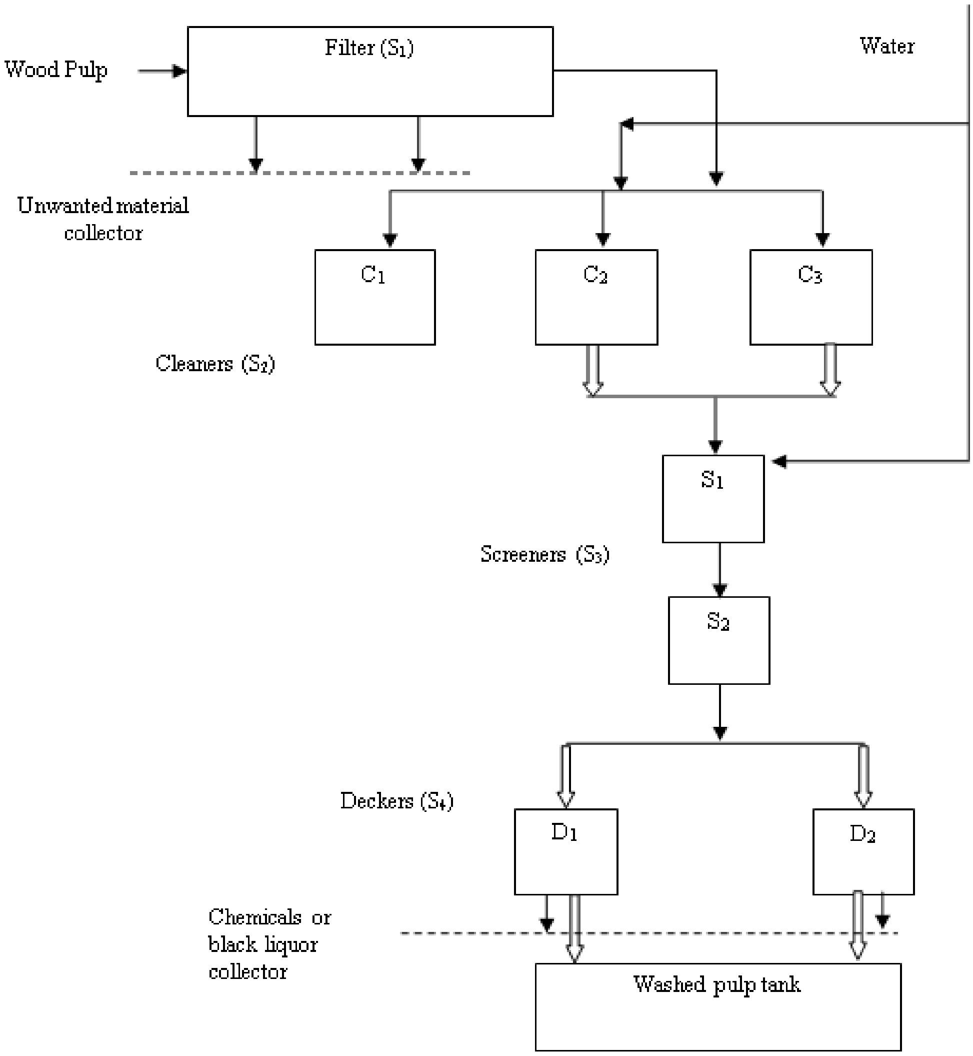

Figure 2: *The washing unit*

4.1. Reliability Analysis

The basic arrangement of the washing unit is modelled by PN model, which is depicted by constituent structure in series/parallel combination with OR/AND transitions, shown in Figure 3. The steps associated with the fuzzy λ-τ approach are presented in following subsections.

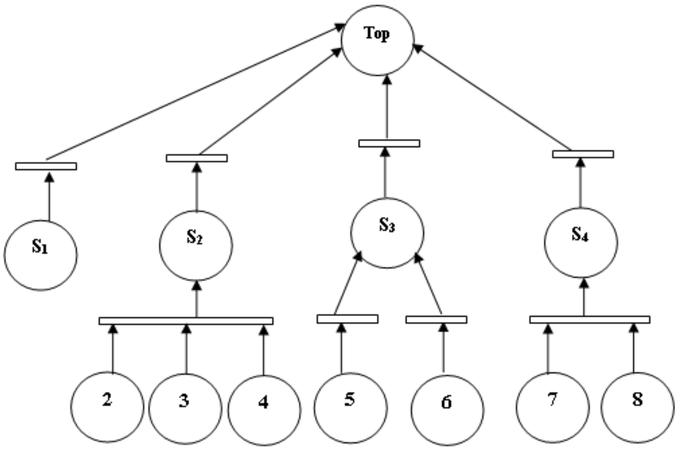

Figure 3: *PN model of washing unit*

4.1.1. Data Collection

The data regarding the failure rate (λ_k) and repair time (τ_k) for each component of various subsystems acquired from the maintenance logbook/historical system records and analyzed by maintenance professionals [23], is represented in Table 1.

Table 1: *Data for λ_k and τ_k*

Subsystems	λ_k (Failures / h)	τ_k (h)
Filter (S_1) (k=1)	1×10^{-3}	3
Cleaner (S_2) (k=2,3,4)	3×10^{-3}	2
Screener (S_3) (k=5,6)	5×10^{-3}	3
Decker (S_4) (k=7,8)	5×10^{-3}	3

4.1.2. Fuzzification of Data

The data collected from various resources is inaccurate, imprecise and ambiguous as it is acquired under different types of operating and environmental conditions. As a consequence, uncertainties in failure/repair data of each component/subsystem of washing unit are quantified by TrFNs at distinct spreads (±15%, ±25% and ±40%). Figure 4 depicts the failure rate (λ_1) and repair time (τ_1) of the filter subsystem (S_1) as TrFNs at ±15% spread.

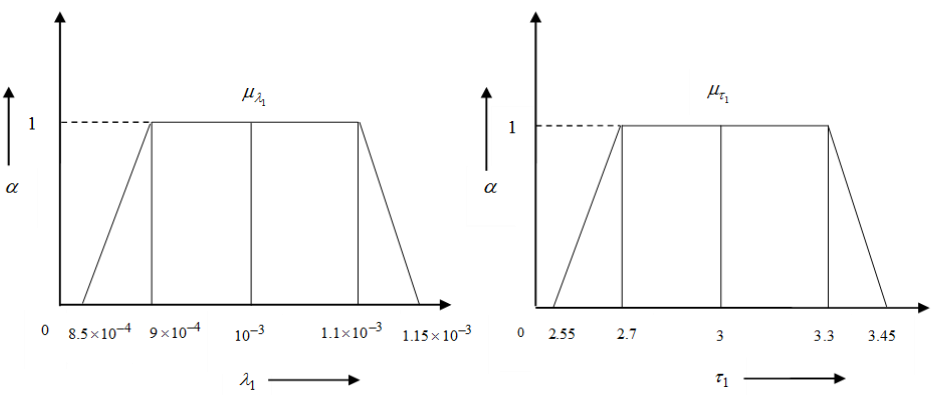

Figure 4: *TrFNs for λ_1 and τ_1 of filter subsystem at ±15% spread*

4.1.3. Reliability Parameters Estimation

After acquiring fuzzified values for λ and τ for all basic components of the washing unit, the fuzzy values for λ and τ of the top position in the PN model of the washing unit are computed by the interval expressions of AND/OR transitions given in equations (4-7). The interval expressions of TrFNs have been calculated by applying interval arithmetic operations on the respective basic expressions of λ and τ for AND/OR gates demonstrated in Table 2 together with the extension principle and alpha-cut.

Table 2: *Basic expressions of λ and τ*

Logic gate	λ_{OR}	τ_{OR}	λ_{AND}	τ_{AND}
n-input gate expression	$\sum_{k=1}^{n} \lambda_k$	$\frac{\sum_{k=1}^{n} \lambda_k \tau_k}{\sum_{k=1}^{n} \lambda_k}$	$\prod_{l=1}^{n} \lambda_l \left\{ \sum_{k=1}^{n} \prod_{\substack{l=1 \\ k \neq l}}^{n} \tau_l \right\}$	$\frac{\prod_{k=1}^{n} \tau_k}{\sum_{l=1}^{n} \left\{ \prod_{\substack{k=1 \\ k \neq l}}^{n} \tau_k \right\}}$

Interval expression AND transition

$$\lambda^{\alpha} = \begin{bmatrix} \prod_{k=1}^{n}\{(\lambda_{k2}-\lambda_{k1})\alpha+\lambda_{k1}\} . \sum_{l=1}^{n}\left\{\prod_{\substack{k=1 \\ k\neq l}}^{n}\{(\tau_{k2}-\tau_{k1})\alpha+\tau_{k1}\}\right\}, \\ \prod_{k=1}^{n}\{\lambda_{k4}-(\lambda_{k4}-\lambda_{k3})\alpha\} . \sum_{l=1}^{n}\left\{\prod_{\substack{k=1 \\ k\neq l}}^{n}\{\tau_{k4}-(\tau_{k4}-\tau_{k3})\alpha\}\right\} \end{bmatrix}, \tag{4}$$

$$\tau^{\alpha} = \left[\frac{\prod_{k=1}^{n}\{(\tau_{k2}-\tau_{k1})\alpha+\tau_{k1}\}}{\sum_{l=1}^{n}\left[\prod_{\substack{k=1 \\ k\neq l}}^{n}\{\tau_{k4}-(\tau_{k4}-\tau_{k3})\alpha\}\right]}, \frac{\prod_{k=1}^{n}\{\tau_{k4}-(\tau_{k4}-\tau_{k3})\alpha\}}{\sum_{l=1}^{n}\left[\prod_{\substack{k=1 \\ k\neq l}}^{n}\{(\tau_{k2}-\tau_{k1})\alpha+\tau_{k1}\}\right]} \right]. \tag{5}$$

Interval expression OR transition

$$\lambda^{\alpha} = \left[\sum_{k=1}^{n}\{(\lambda_{k2}-\lambda_{k1})\alpha+\lambda_{k1}\},\ \sum_{k=1}^{n}\{\lambda_{k4}-(\lambda_{k4}-\lambda_{k3})\alpha\}\right], \tag{6}$$

$$\tau^{\alpha} = \left[\frac{\sum_{k=1}^{n}[\{(\lambda_{k2}-\lambda_{k1})\alpha+\lambda_{k1}\} . \{(\tau_{k2}-\tau_{k1})\alpha+\tau_{k1}\}]}{\sum_{k=1}^{n}\{\lambda_{k4}-(\lambda_{k4}-\lambda_{k3})\alpha\}}, \frac{\sum_{k=1}^{n}[\{\lambda_{k4}-(\lambda_{k4}-\lambda_{k3})\alpha\} . \{\tau_{k4}-(\tau_{k4}-\tau_{k3})\alpha\}]}{\sum_{k=1}^{n}\{(\lambda_{k2}-\lambda_{k1})\alpha+\lambda_{k1}\}} \right]. \tag{7}$$

To assess the behavior of the washing unit quantitatively, the reliability parameters including, failure rate (λ), repair time (τ), mean time between failure (MTBF), expected number of failures (ENOF), reliability and availability are estimated utilizing the terms in Table 3 at spread levels ±15%, ±25% and ±40% for various degrees of membership.

Table 3: *Reliability parameters*

Reliability parameters	Expressions
MTTR	$\tau = \frac{1}{\mu}$
MTTF	$\frac{1}{\lambda}$
MTBF	$\tau + \frac{1}{\lambda}$
ENOF	$\frac{\lambda \mu t}{(\lambda+\mu)} + \frac{\lambda^2}{(\lambda+\mu)^2}[1-e^{-(\lambda+\mu)t}]$
Reliability	$e^{-\lambda t}$
Availability	$\frac{1}{(\lambda+\mu)}\left[\mu+\lambda e^{-(\lambda+\mu)t}\right]$

The variations of reliability parameters of washing unit at 15% spread for TrFN and TFN are depicted in Figures 5 (a-f).

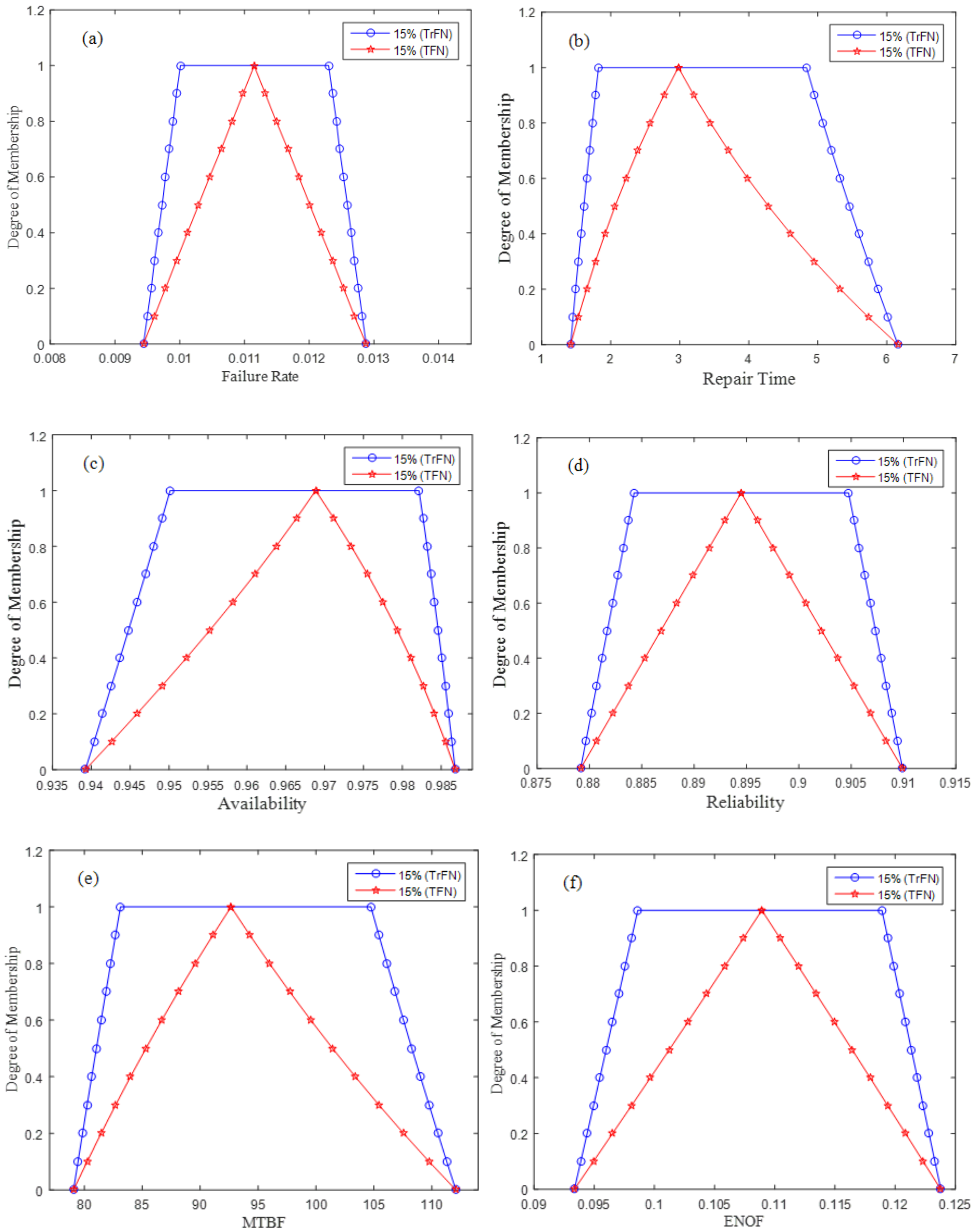

Figure 5: *Fuzzy reliability parameters using TrFN and TFN at ±15% spread*

4.1.4. Defuzzification

The estimated fuzzy values of different reliability parameters should be defuzzified in order to implement maintenance activities. Among various defuzzification techniques, such as the bisector, weighted average, center of area, centroid, middle of max, etc. the center of area technique has been chosen here for defuzzification of reliability parameters, as this technique is easy to implement. The defuzzified value ($\tilde{x}$) for fuzzy set $\tilde{A}$ is described as

$$\tilde{x} = \frac{\int_{x_1}^{x_2} x\mu_{\tilde{A}}(x)dx}{\int_{x_1}^{x_2} \mu_{\tilde{A}}(x)dx} \tag{8}$$

where, $\mu_{\tilde{A}}(x)$ is the membership function of $\tilde{A}$ described on [x_1, x_2]. The crisp and defuzzified results of reliability parameters for washing unit with three considered spreads are demonstrated in Table 4.

Table 4: *Crisp and defuzzified results*

Reliability parameters	**Crisp results**	**Fuzzy Numbers**	**Defuzzified results**		
			±15%	±25%	±40%
Failure Rate	0.011150	Trapezoidal	0.011159	0.011167	0.011194
		Triangular	0.011157	0.011167	0.011197
Repair Time	2.979753	Trapezoidal	3.577073	4.573931	8.204359
		Triangular	3.520117	4.631914	8.406379
Reliability	0.894518	Trapezoidal	0.894518	0.894562	0.894673
		Triangular	0.894530	0.894567	0.894687
Availability	0.968846	Trapezoidal	0.964473	0.959521	0.950455
		Triangular	0.964950	0.959287	0.949457
MTBF (×10^2)	0.926632	Trapezoidal	0.948037	0.981285	1.087302
		Triangular	0.946023	0.983636	1.096407
ENOF	0.108919	Trapezoidal	0.108659	0.108340	0.107706
		Triangular	0.108673	0.108323	0.107643

Table 5: *Percent changes in defuzzified values for TrFN and TFN*

Change in spread	Fuzzy Numbers	Percent changes in defuzzified values					
		Failure rate	Repair time	Reliability	Availability	MTBF	ENOF
15% to 25%	TrFN	0.07 (↑)	27.87 (↑)	0.005 (↑)	0.51 (↓)	3.51 (↑)	0.29 (↓)
15% to 25%	TFN	0.09 (↑)	31.58 (↑)	0.004 (↑)	0.59 (↓)	3.98 (↑)	0.32 (↓)
25% to 40%	TrFN	0.24 (↑)	79.37 (↑)	0.012 (↑)	0.95 (↓)	10.80 (↑)	0.59 (↓)
25% to 40%	TFN	0.27 (↑)	81.49 (↑)	0.013 (↑)	1.03 (↓)	11.47 (↑)	0.63 (↓)

4.2. Behavioral Study

The fluctuations of fuzzy reliability parameters at 15% spread have been presented graphically in Figures 5 (a-f). The obtained membership curves are deformed trapeziums, with parabolic non parallel sides since fuzzy mathematics transforms left and right sides of membership curves of TrFN into curved ones [24]. The crisp and defuzzified results of reliability parameters for three distinct spread levels, obtained using TrFN and TFN both, in fuzzy λ-τ approach have been presented in Table 4. When the spread level increases, an increasing trend is observed in defuzzified values of parameters failure rate, repair time, reliability and MTBF, while, a decreasing trend is observed in values of system availability and ENOF in case of TrFN and TFN both. Also, the results obtained by the fuzzy λ-τ approach using TrFN follow the same pattern (increase or decrease) as those obtained by using TFN.

Table 5 presents the percent increase or decrease in values of different reliability parameters with spread level increase for both TrFN and TFN. It is observed that for spread increase from 15% to 25%, in case of TrFN, the failure rate of the system increases by 0.07%, while, for TFN, it increases by 0.09%. For a spread change from 25% to 40%, the failure rate increases by 0.24% for TrFN, while, for TFN, it increases by 0.27%. Similarly, for other reliability parameters, for the spread expansion from 15% to 25%, in case of TrFN, the repair time increases by 27.87% and MTBF increases by 3.51%, while, system availability decreases by 0.51% and ENOF decreases by 0.29%. On the other hand, in case of TFN, repair time increases by 31.58% and MTBF increases by 3.98%, while system availability and ENOF decrease by 0.59% and 0.32%, respectively. A very marginal and almost same increase is observed in system reliability for both TrFN and TFN. Similar inferences are drawn for spread expansion from 25% to 40% from Table 5. It is clear from these observations that when uncertainty level increases in terms of spread increase, the trend of reliability parameters (increase or decrease) remains almost the same for both TrFN and TFN. Therefore, the results obtained through the fuzzy λ-τ approach with TrFN are conservative in nature, which might be useful for system specialist/analysts for the future plan of implementation. Therefore, instead of crisp results, the maintenance plan should be based on defuzzified results.

5. Conclusion

The behavior of the washing unit in a paper plant has been analyzed in this study using the fuzzy λ-τ approach with TrFN. Using the fuzzy approach, some reliability parameters involving failure rate, repair time, MTBF, ENOF, reliability and availability are estimated and the trend of reliability parameters is evaluated for performance and behavior study of washing unit. Further, the obtained results by the fuzzy λ-τ approach with TrFN are compared with the results of the fuzzy λ-τ approach based on TFN. The implications of this fuzzy reliability approach to industry maintenance and operation planning are quite significant. Based on these investigations, suitable maintenance policy can be established that will assist maintenance managers in improving system performance by implementing appropriate preventive maintenance procedures. As a result, it will help in achieving a long time system availability and maximizing overall productivity of the paper plant.

Declaration of Conflicting Interests

The authors declare that there is no conflict of interest.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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