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Structured Framework for Reliability of an Industrial System Using Fuzzy Approach

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Abstract: ***Over the years, reliability of a system is one such term that has gained importance pertaining to the industrial systems. This accounts for unforeseen circumstances that can occur to the machines at any time during the production. Hence, to prevent this, computational method is applied to determine the reliability parameters which predicts the current status of the machines. This paper tends to present the evaluation with the help of Petri Net (PN) and Fault Tree Analysis (FTA) to represent the system and analyses them with used Fuzzy Lambda-Tau technique (FLT). The structured framework provides an insight as to how the investigation is done and deduces the results. The defuzzification is performed at different spread 15%, 25% and 60% of the current crisp value in the system to perform the in-depth analysis of the system. The results are then subjected to further investigation to the maintenance engineer which eventually leads to plan an appropriate maintenance policy for improving the overall performance of the production unit.***

Keywords: Fault tree analysis, Petri net, Fuzzy lambda tau, ENOF, Reliability, Availability

1. Introduction

Over the years, research on reliability has not been very significant and there exists quite a complex nature of its parameters with regard to it. Various methodologies and techniques have been extensively used in this field in order to analyze the system. The machines in the system are arranged in the logical manner which helps us to study about them effectively and thereby knowing the purpose of each machines. This aids to the improvement and analysis of the critical behavior pertaining to the various factors of reliability and caters for a better prospect of the productivity of the firm. Petri Net (PN) and Fault Tree Analysis (FTA) are drawn hand in hand for the plant layout which then combines with the logic of fuzzy lambda tau methodology to deliver certain values.

The reliability parameters in accordance with the fuzzy techniques had seen vast development when speaking about the process industries. The modifications and alterations developed are quite significant and guides through the improvement of the concerned issue. In 1989, keller and zaitri used fuzzy extensively to study and evaluate the imprecise data. The methodology of failure mode effect analysis was implied which diagnosed the problems. The concept of fuzzy logic slowly gained momentum and reached in the field of reliability. The techniques of fuzzy logic are very well suited for the vague nature of reliability. Therefore, Nahman, in 1997, established a reliability network in accordance to the customer's requirement. Knezevic and Odoom 2000, modelled a reliability analysis with petri net model instead of fault tree. This paves way for efficient generation of minimal cut and path sets. The spreads signify the repairable conditions of the technical system Later on, in 2004, zafiropolus and Dialynas introduced the concept of fuzzy logic in the field of electronic devices. In 2006 gofuku addresses that FTA is a top-down approach to evaluate the risky components in the overall system and to prevent the happening of undesirable events. komal and Sharma 2014, predicted the behavior of washing system using the methodology of fuzzy lambda tau and found out that design of the system is insufficient if it is analyzed with empirical methods. They computed various reliability parameters in a washing unit which were analyzed with help of three methodologies Fuzzy lambda tau with the combination of genetic algorithm and neural networks these hybrid techniques are quite useful in revealing about the maintenance strategies. Garg in 2013 performed reliability on vague lambda tau methodology which consists set of three regions. This made the evaluation more extensive. In 2014, dilbag performed the reliability analysis of a thermal power plant in which the different reliability parameters were determined using lambda tau technique. The critical analysis revealed the trend which identifies the status of the machine. Later on, Vishwakarma and sharma in 2015, performed intuitionistic fuzzy which includes the concept of vague set theory. Then, reliability indices are calculated using lambda tau and behavior of the system is predicted. Komal et al in 2015, performed reliability analysis with concurrency of two techniques i.e FLT and GABLT (Genetic Algorithm based Lambda Tau) .sensitivity analysis and ranking was estimated to find out the order of system failure and their maintenance requirement accordingly, Similarly, in 2016, Iqbal and uduman worked on the reliability of a paper plant which was analyzed with the help of functions and numerical analysis. Thus, these prove that fuzzy is a versatile tool.

2. Framework Model

Fig 1 depicts a schematic representation of the framework that is applied for this research work. These include three sections which are eventually categorized according to the work performed in that area.

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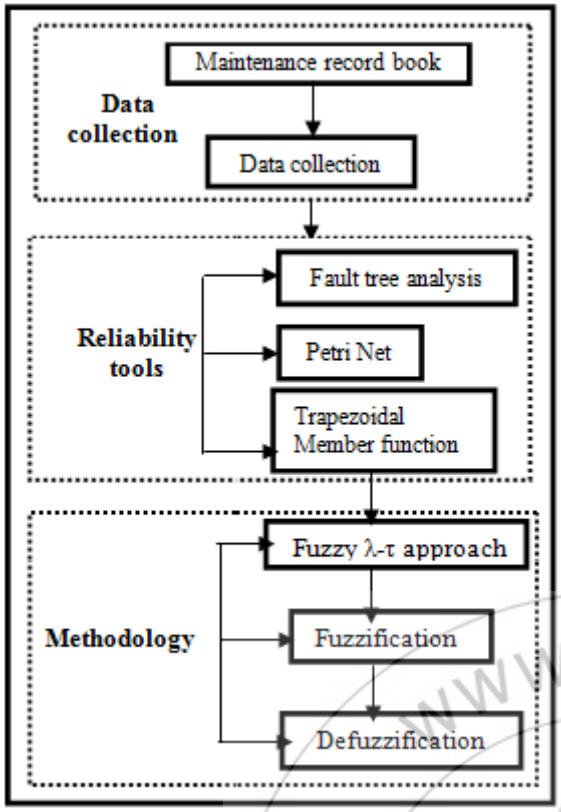

Fig.1. Structured framework of Reliability approach

3. Methodology

3.1 PN Model

Petri net make use of diagraph to describe cause and effect relationship between conditions and events. According to Ajay Kumar 2009, it consists of static as well as dynamic part in which the static part consists of three objects and whereas the dynamic part is the marking. Classical petri net is used for the investigation of qualitative and logical properties of the system where as the quantitative analysis time concept is needed to be considered. In the present study, static part of the PN has been used to analyze the behavior of the system as described by Peterson.

3.2 FTA Model

It is tool for a reliability analysis of a complex system and it is associated with failure probability of various events with their effect on the system performance. A fault tree model is a logical representation of AND/OR gates based on the components in a system. In 2008, Souza and Alvares analyzed fault tree in relation with Failure Mode Effect Analysis. These two tools can be used to form a systematic and standardized evaluation of failures thereby establishing its consequences. Basically, the fundamental concept of the FTA consists of the interpretation of a physical system in a structured logical diagram which makes complex industrial systems easy to understand. Volkanvoski in 2009 said that fault tree is mathematically represented by a set of Boolean equations that aids in developing the equations pertaining to system failures. In 2013, waghmode and Patil constructed FTA model for lathe machine to have a broader perspective to consider its failures.

3.3 Fuzzy Methodology

Fuzzy Lamda-Tau methodology is traditional method for analyzing system fuzzy reliability. It makes use of the basic event (and or end gates) represented by trapezoidal fuzzy number. However, komal and sharma 2014, observed that this method may become more complex if more number of components are presenting the system. The concept of alpha cut set is to establish a bridge between fuzzy set theory and crisp set theory. Sonam 2015, says Alpha-cut set of the fuzzy set is a crisp set that contains all those elements of the universal set whose membership value in fuzzy set are greater than or equal to the specified value of alpha.

Liou and Wang 1992 defines, the fuzzy number A = [a, b, c, d; 1] is a trapezoidal fuzzy number, denoted by (a, b, c, d; 1), if its membership function f_A is given by

$$f_A(X) = \begin{cases} (x - a)/(b - a), & a \le x \le b, \\ 1, & b \le x \le c, \\ (x\ d)/(c-d), & c \le x \le d, \\ O, & \text{otherwise}, \end{cases}$$

It is obvious that in $f^L_A(x) = (X -- a)/ (b - a)$, and $f^R_A(x) = (X -- d)/ (c - d)$. The inverse functions of $f^L_A(x)$ and f^R_A are $g^L_A(y) = a+ (b-a)\ y$ and $g^R_A(y) = d+ (c-d)\ y$, where y e [0, 1]. Thus

$I_L(A) = \int g^L_A(y)\ dy = [a + (b - a)\ y]\ dy$
$= ½\ (a + b)$,
And
$I_R(A) = \int g^R_A(y)\ dy = [d + (c - d)\ y]\ dy$
$½\ (c + d)$.

For simplicity of calculation, given α € [0, 1], the total integral value of the trapezoidal fuzzy number A = (a, b, c, d; 1) can be directly obtained without integration:
$I^{\alpha}_T(A) = ½[\ \alpha\ (c + d) + (1 - \alpha)(a + b)]$.

3.4 Ranking generalized fuzzy numbers with trapezoidal membership functions

Chen 1985 proposed that there are n generalized fuzzy numbers A1, A2, ... A_n with trapezoidal membership functions $A_i = (c_i, a_i, b_i, d_i; w_i)$. The trapezoidal membership function of generalized fuzzy number A, is given by

$$f_{Ai}(X) = \begin{cases} w_i\ (x - c_i)/(a_i - c_i), & c_i \le x \le a_i, \\ wi\ , & a_i \le x \le b_i, \\ w_i\ (x- d_i)/(b_i - d_i), & b_i \le x \le d_i, \\ O, & \text{otherwise}, \end{cases}$$

The membership functions of maximizing set M and minimizing set G are given by

$$F_M(x) = \begin{cases} W\ [(x-x_{min})/(x_{max}-x_{min})]^k, & x_{min} \le x \le x_{max} \\ 0, & \text{otherwise}, \end{cases}$$

And

$$F_G(x) = \begin{cases} W\ [(x-x_{max})/(x_{min}-x_{max})]^k, & x_{max} \le x \le x_{min} \\ 0, & \text{otherwise}, \end{cases}$$

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4. Case Study

The research focuses on the different machines required to manufacture centrifugal pump that converts the kinetic energy to hydrodynamic energy. It enables liquid to flow from low pressure to high pressure at a faster rate. It consists of casing (volute, circular), bearing, shaft rod and an impeller.

The raw material is employed to the lathe machine system (LM1, LM2, and LM3) where the impeller and the gland plate is machined. Depending upon the specified dimensions, the lathe machine removes around 5-7mm of the extra material and it also performs a circular operation on the impeller and the gland plate. Two vertical boring (VBM 4, VBM 5) performs the boring process to the upper and lower half of the material which forms the circular pattern in the material. The upper and lower half then goes through tapping operation in the tapping machine (T6) where the threading and cutting procedure is performed with the help of the tapping tool. In the vertical radial drilling machine (RDM 7, RDM 8, RDM 9, RDM 10), drilling takes place for 30 holes of 28mm in diameter which are crafted on the upper and the lower half for assembling the nuts and bolts. It takes around 3 minutes to drill each hole. Thus, the total time required for this process is 90 minutes. Then a dwell pin is formed on the upper and the lower half with 4 holes of 12mm in diameter and 4 holes of 16mm in diameter. Vertical lathe machine (VLMS 12, VLM 13) has one of the longest processes in the total production process where the upper and lower half are employed in machine which remove 10-15mm material from the work piece and facing and threading processes are also performed. Slotting machine (SM11) preforms the slotting process on the upper and lower half where keyways of a cylindrical form in the material is formed according to the specific dimensions.

After the whole process, the finished is material is again sent to the inspection department to check out the minute defects and if there is a defect it is again sent back to the manufacturing unit. The final product is then sent to the assembly department where the impeller, gland plates, upper and lower half, bearing housing, shaft rods are assembled to produce the desired centrifugal pump.

In hydro test, the assembled parts are employed to the various machines to check out if there is any kind of leakage in the product. Performance test determines the pressure produced by the pump are within the desired pressure range or deviating and also test the head of the centrifugal pump.

5. Analysis of Fuzzy Numbers

The data received form the company is converted into a precise form so that they can be used as an input of trapezoidal fuzzy number. Using the principle of extension which include α-cut, the figure is drawn for failure rate and repair rate. The interval arithmetic operations using the transition expressions of AND /OR gates in accordance to the lambda-tau expressions are deduced from the PN model.

5.1 Expressions

Expressions for AND transitions

$$\lambda^{(\alpha)} = \left[\prod_{i=1}^{n} \{(\lambda_{i2} - \lambda_{i1})\alpha + \lambda_{i1}\} . \sum_{j=1}^{n} \left[\prod_{\substack{i=1 \\ i \neq j}}^{n} \{(\tau_{i2} - \tau_{i1})\alpha + \tau_{i1}\} \right], \prod_{i=1}^{n} \{-(\lambda_{i3} - \lambda_{i2})\alpha + \lambda_{i3}\} . \sum_{j=1}^{n} \left[\prod_{\substack{i=1 \\ i \neq j}}^{n} \{(\tau_{i3} - \tau_{i2})\alpha + \tau_{i3} \right] \right]$$

$$\tau^{(\alpha)} = \left[\frac{\prod_{i=1}^{n} \{(\tau_{i2} - \tau_{i1})\alpha + \tau_{i1}\}}{\sum_{j=1}^{n} \left[\prod_{\substack{i=1 \\ i \neq j}}^{n} \{-(\tau_{i3} - \tau_{i2})\alpha + \tau_{i3}\} \right]}, \frac{\prod_{i=1}^{n} \{(\tau_{i3} - \tau_{i2})\alpha + \tau_{i3}\}}{\sum_{j=1}^{n} \left[\prod_{\substack{i=1 \\ i \neq j}}^{n} \{-(\tau_{i2} - \tau_{i1})\alpha + \tau_{i1}\} \right]} \right]$$

Expressions for OR transitions

$$\lambda^{(\alpha)} = \left[\sum_{i=1}^{n} \{(\lambda_{i2} - \lambda_{i1})\alpha + \lambda_{i1}\}, \sum_{i=1}^{n} \{-(\lambda_{i3} - \lambda_{i2})\alpha + \lambda_{i3}\} \right],$$

$$\tau^{(\alpha)} = \left[\frac{\sum_{i=1}^{n} \left[\{\lambda_{i2} - \lambda_{i1})\alpha + \lambda_{i1} . \{(\tau_{i2} - \tau_{i1})\alpha + \tau_{i1}\} \right]}{\sum_{i=1}^{n} \{-(\lambda_{i3} - \lambda_{i2})\alpha + \lambda_{i3}}, \frac{\sum_{i=1}^{n} \left[\{-\lambda_{i3} - \lambda_{i2})\alpha + \lambda_{i3}\} . \{-(\tau_{i3} - \tau_{i2})\alpha + \tau_{i3}\} \right]}{\sum_{i=1}^{n} \{(\lambda_{i2} - \lambda_{i1})\alpha + \lambda_{i1}\}} \right]$$

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Some basic expressions for fuzzy methodology

Gate	λ_{AND}	τ_{AND}	λ_{OR}	τ_{OR}
Expressions	$\prod_{j=1}^{n}\lambda_j\left[\sum_{i=1}^{n}\prod_{\substack{j=1\\ i\neq j}}^{n}\tau_j\right]$	$\frac{\prod_{i=1}^{n}\tau_i}{\sum_{j=1}^{n}\left[\prod_{\substack{i=1\\ i\neq j}}^{n}\tau_i\right]}$	$\sum_{i=1}^{n}\lambda_i$	$\frac{\sum_{i=1}^{n}\lambda_i\tau_i}{\sum_{i=1}^{n}\lambda_i}$

5.2 Model

Working model is shown in Fig 2 which systematically displays the process flow that takes place through each machine. Hauptmanns in 2011 has performed the reliability data acquisition and detected the component failure of the process plant. The statistics were complicated and tedious for estimation. But, in order to determine the reliability of the machines considered here for the centrifugal pump, two models were developed. They are petri net model (PN) and fault tree analysis (FTA) as shown in fig 3 and fig 4.

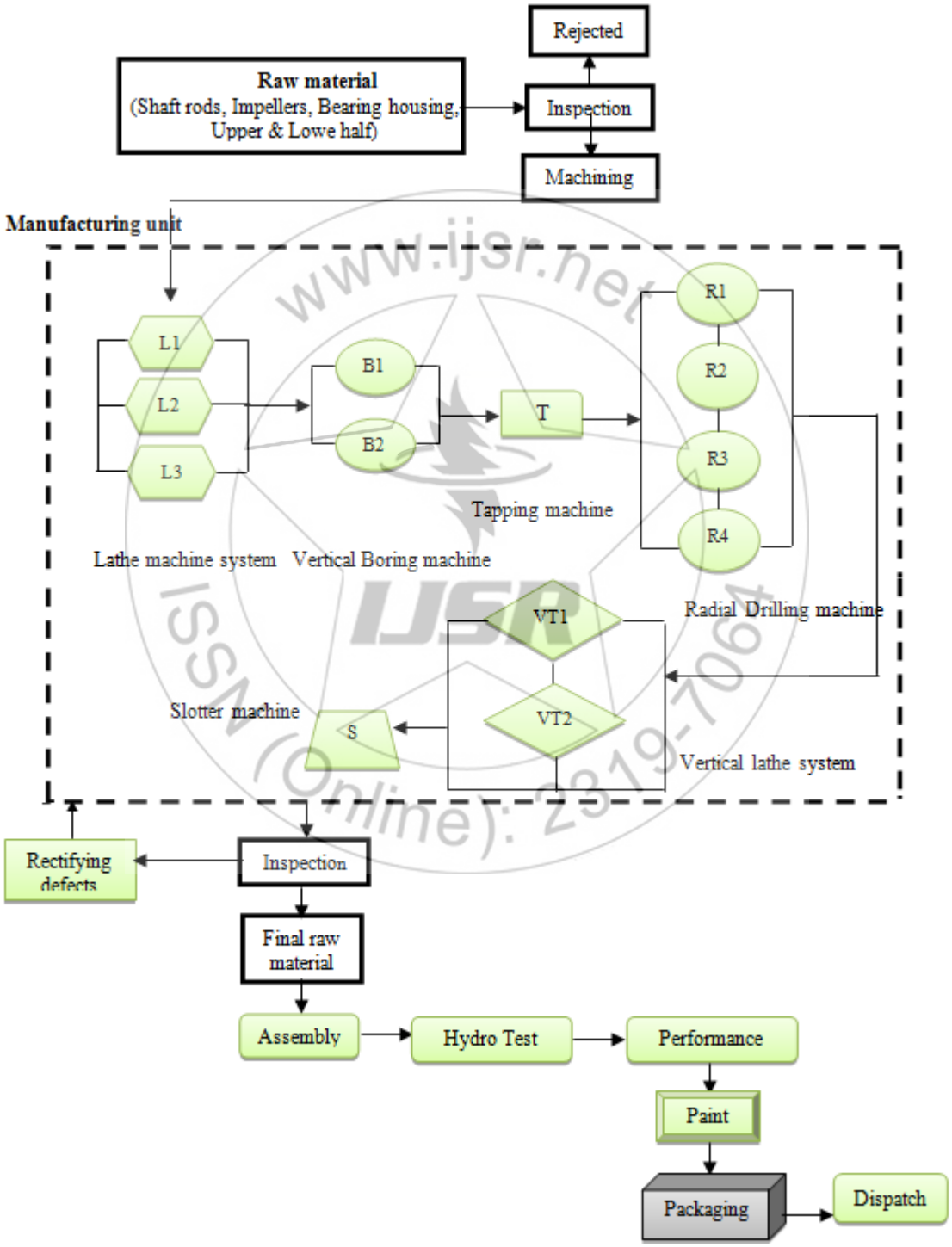

Figure 2: Integrated framework (working model)

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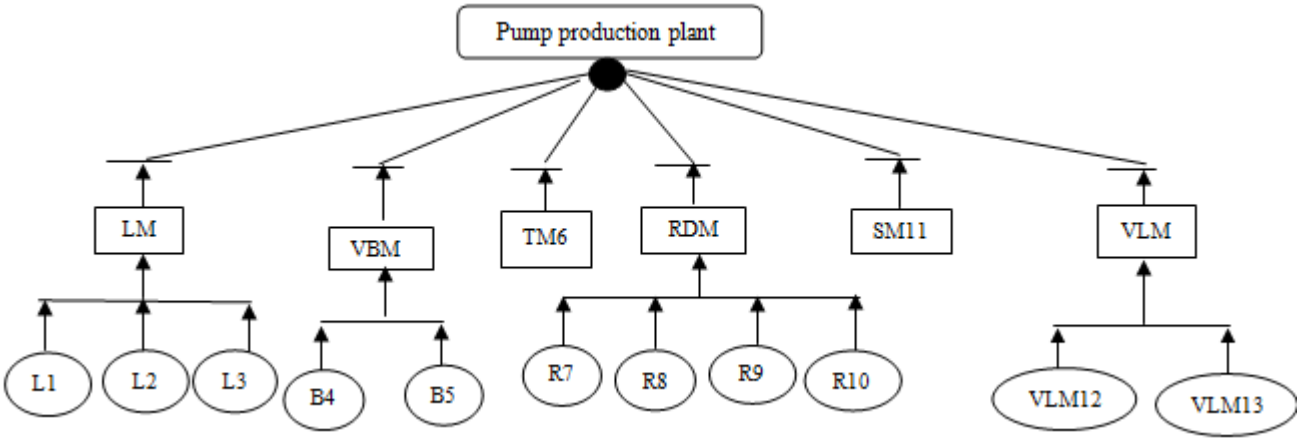

Figure 3: Petri Net model for Pump Production Plant

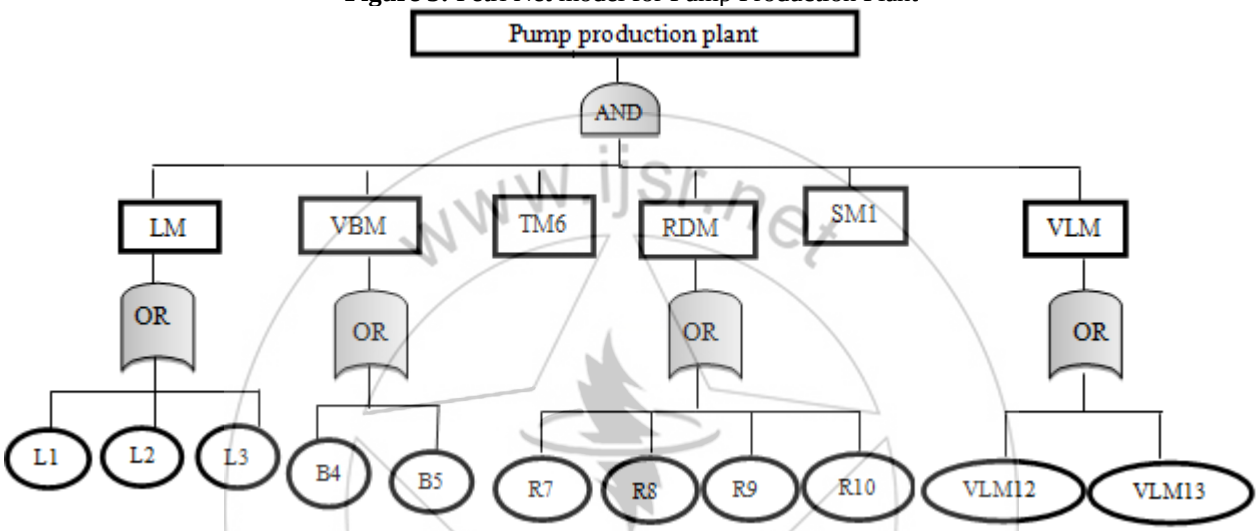

Figure 4: FTA model for Pump Production Plant

5.4 Analysis of crisp value

Firstly, the data of failure and repair time of each machine in the system was obtained from the maintenance record book. These data were in the informal state and were difficult to compute. So, the data was converted into Crips value. Moreover, the extension principle of α-cut function and basic expression of AND/OR gate of the λ-τ methodology was applied on the trapezoidal member to obtain the intervals of crisp value using the FTA model. The behavior of the system was executed with the PN model.

Table 1: Crisp value

Machines	Failure rate (λ_i) failure/hrs	Repair time (τ_i) hrs
Lathe (i=1)	3.52×10^{-4}	3
Lathe (i=2)	3.52×10^{-4}	1
Lathe (i=3)	2.88×10^{-4}	2
Vertical boring machine (i=4,5)	2.24×10^{-4}	1
Tapping machine (i=6)	3.84×10^{-4}	1
Radial drilling machine (i=7,8,9,10)	2.88×10^{-4}	1
Slotter machine (i=11)	2.24×10^{-4}	2
Vertical lathe machine (i=12,13)	1.60×10^{-4}	1

Figure 5: Input Fuzzy trapezoidal number for Failure Rate

From the figure 5, 6 it is seen that the crisp data is fuzzified.

The concept of alpha cut using the extension principle derives the in-between values that provides a clear picture to understand the interval and draw out the trapezoidal membership function.

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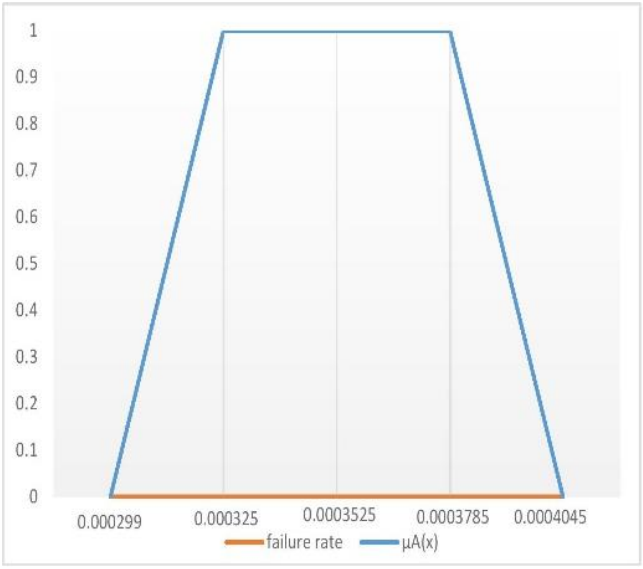

Figure 6: Input Fuzzy trapezoidal number for Repair Time

6. Reliability Evaluation

Table 2: Reliability Expression

Reliability Parameters	Expressions
Mean time between failure	$\frac{1}{\lambda_s}$
Mean time to Repair	$\frac{1}{\mu_s}$
Availability	$\frac{\mu_s}{\mu_s+\lambda_s}+\frac{\lambda_s}{\mu_s+\lambda_s}e^{-(\mu_s+\lambda_s)t}$
Reliability	$e^{-\lambda_s t}$
Mean time between failures	MTTF + MTTR
Expected Number of failures	$\frac{\lambda_s\mu_s t}{\mu_s+\lambda_s}+\frac{\lambda_s^{\,2}}{(\mu_s+\lambda_s)^2}\left[1-e^{-(\mu_s+\lambda_s)t}\right]$

6.2 Deduced equation derived from FTA for failure rate and repair time: -

$\lambda_s = \lambda_1\lambda_2\lambda_3(\tau_{12}+\tau_{23}+\tau_{13}) + \lambda_4\lambda_5(\tau_4+\tau_5) + \lambda_6 + \lambda_7\lambda_8\lambda_9\lambda_{10}(\tau_{7,8,9}+\tau_{7,9,10}+\tau_{8,9,10}+\tau_{8,10,7)} + \lambda_{11} + \lambda_{12} + \lambda_{13}$

$\tau_s = (\lambda_1\lambda_2\lambda_3)\ x\ (\tau_1\tau_2\tau_3) + \lambda_4\lambda_5\tau_4\tau_5 + \lambda_6\tau_6 + (\lambda_7\lambda_8\lambda_9\lambda_{10}\ x\ \tau_7\tau_8\tau_9\tau_{10}) + \lambda_{11}\tau_{11} + \lambda_{12}\tau_{12} + \lambda_{13}\tau_{13}$

6.3 Reliability parameter computation

Table 3 and 4 shows the various reliability parameters at 15% for left and right side spread. Similarly, these parameters are also computed for left and right spreads at 25%, 60% after the crisp data is fuzzified. This is done for alpha cuts ranging from 0 to 1 with an interval of 0.1. After this, defuzzification is performed using the method of Centre of gravity (COG) for all the parameters at the spreads of 15%, 25%, 60%. Later on, a comparison is drawn out amongst these for the behavioral analysis of the systems in the production unit.

Table 3: 15% Left side spread

Dof	*Failure Rate*	*Repair Time*	*Availability*	*Unavailability*	*Reliability*	*Unreliability*	*MTBF*	*ENOF*
1	0.000992101	1.22573277	0.99878543	0.001214573	0.96109307	0.038906932	1009.1879	0.0396373
0.9	0.000976896	1.20768377	0.99882161	0.001178392	0.96167775	0.038322246	1024.8576	0.0390312
0.8	0.000963292	1.18906884	0.99885589	0.00114411	0.96220121	0.037798786	1039.2957	0.0384889
0.7	0.000948488	1.16981983	0.99889167	0.00110833	0.96277117	0.03722883	1055.4795	0.0378987
0.6	0.000932684	1.15241133	0.99892632	0.001073681	0.96337999	0.036620008	1073.3271	0.0372684
0.5	0.000918079	1.1301544	0.9989635	0.001036496	0.96394294	0.036057062	1090.3605	0.0366862
0.4	0.000902276	1.11580886	0.99899424	0.001005755	0.96455247	0.035447526	1109.4241	0.0360558
0.3	0.000888472	1.09713814	0.99902617	0.000973828	0.9650852	0.034914802	1126.6246	0.0355052
0.2	0.000873869	1.07875037	0.9990582	0.000941798	0.96564911	0.034350891	1145.4153	0.0349227
0.1	0.000858065	1.06053496	0.99909082	0.000909181	0.96625973	0.033740273	1166.473	0.0342922
0	0.000843262	1.04209178	0.99912202	0.000877985	0.96683205	0.033167947	1186.9132	0.0337016

Table 4: 15% Right side spread

Dof	*Failure rate*	*Repair time*	*Availability*	*Unavailability*	*Reliability*	*Unreliability*	*MTBF*	*ENOF*
1	0.000992101	1.22573277	0.998785427	0.00121457	0.961093068	0.0389069	1009.1879	0.0396373
0.9	0.001006109	1.24395134	0.998750014	0.00124999	0.960554696	0.0394453	995.17222	0.0401956
0.8	0.001023114	1.26249721	0.998709987	0.00129001	0.959901524	0.0400985	978.67024	0.0408734
0.7	0.001036115	1.2809487	0.998674549	0.00132545	0.959402487	0.0405975	966.42484	0.0413914
0.6	0.00105012	1.29916955	0.998637575	0.00136242	0.958865193	0.0411348	953.57165	0.0419494
0.5	0.001067125	1.31384516	0.998599926	0.00140007	0.958213185	0.0417868	938.41131	0.0426272
0.4	0.001081931	1.3361569	0.998556458	0.00144354	0.957645863	.0423541	925.60967	0.0432168
0.3	0.001095135	1.35028503	0.998523439	0.00147656	0.957140204	0.0428598	914.47983	0.0437429
0.2	0.001111142	1.37292957	0.998476804	0.0015232	0.956527564	0.0434724	901.34806	0.0443803
0.1	0.001125147	1.38727959	0.99844154	0.00155846	0.955991878	0.0440081	890.1604	0.0449382
0	0.001142154	1.40969492	0.9983925	0.0016075	0.955341744	0.0446583	876.94846	0.0456153

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Table 5: Defuzzifcation at different spreads

Parameter	*Crisp value*	*At 15%*	*At 25%*	*At 60%*
Failure rate	0.000992101	0.000992036	0.000991785	0.000991654
Repair Time	1.225732766	1.225255814	1.224694796	1.209417103
Availability	0.998785427	0.998781758	0.998775433	0.998650372
Unavailability	0.001214573	0.001218198	0.001224567	0.001349628
Reliability	0.961093068	0.961093791	0.961112337	0.96115064
Unreliability	0.038906932	0.038906208	0.038887663	0.03884936
MTBF	1009.187883	1012.544959	1019.274859	1073.340315
ENOF	0.039637306	0.039629683	0.039623471	0.039612298

Table 6: Change in Defuzzification at different spread

0% to 15%	15% to 25%	25% to 60%	Trend
-6.48977E-05	-0.000253346	-0.000131762	decreasing
-0.000389267	-0.000458088	-0.012632278	decreasing
-3.67307E-06	-6.33252E-06	-0.00012523	decreasing
0.002975394	0.005200811	0.092663205	increasing
7.52435E-07	1.9296E-05	3.98514E-05	increasing
-1.86151E-05	-0.000476874	-0.000985942	decreasing
0.003315483	0.006602635	0.050371215	increasing
-0.000192346	-0.000156771	-0.000282058	decreasing

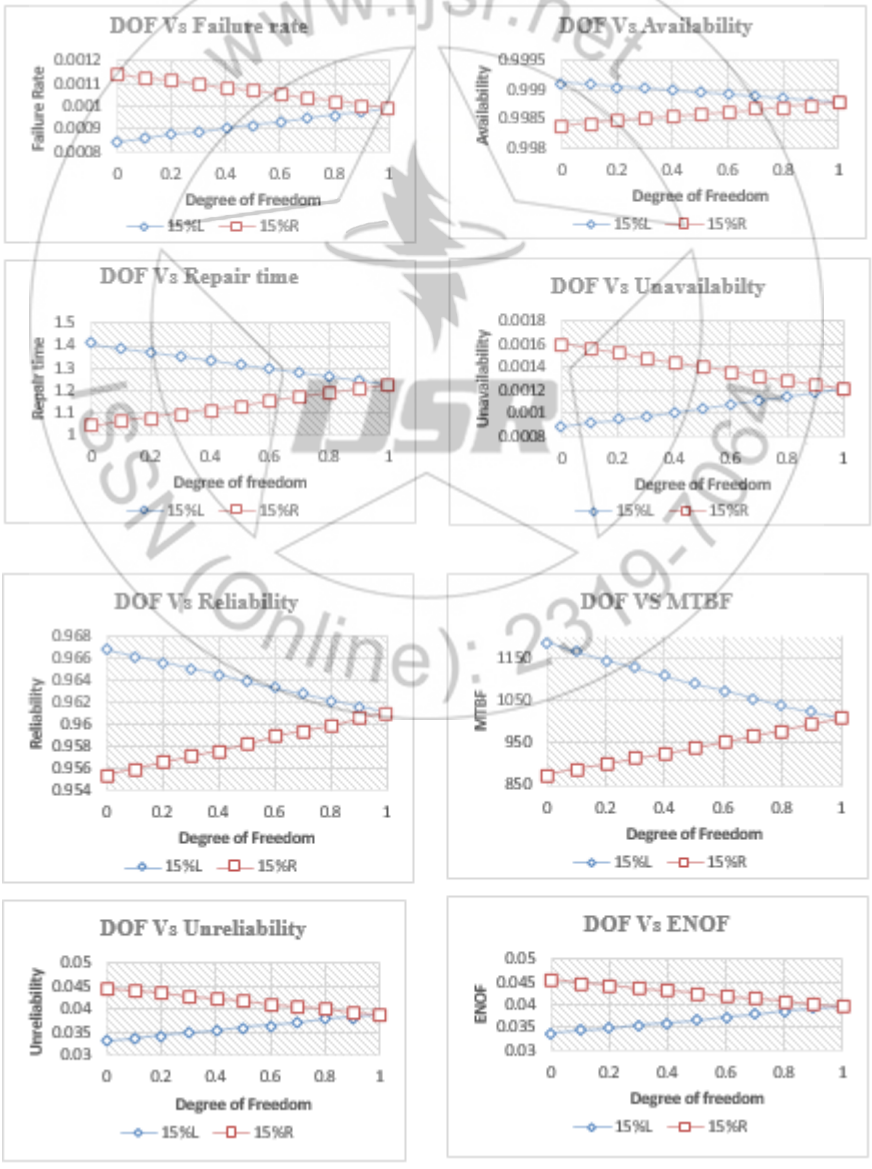

Figure 7: Fuzzy representation of different reliability parameters at 15% spread

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7. Results

The table 5 shows the defuzzification at different spreads and table 6 shows the trends corresponding to each parameter. The crisp value is also denoted to draw out the comparison. The defuzzification method is carried out by centre of gravity method which is computed accordingly for each of the parameter. It is observed that for unavailability, reliability and MTBF, the trend increase. This means, as the spread increases, the values of these parameters increase. The other parameters have the trend decreasing. A series of graph is shown in Fig 7 which shows the patterns obtained by various parameters with the degree of freedom interval of 0.2 to have a pictorial view of the evaluated parameters. Thus, based on these results and observation, the maintenance analyst will select or study upon a defuzzified value which will be suitable to achieve the maximum productivity and efficiency.

8. Conclusion

The in-depth reliability analysis of the components of centrifugal production pump gave us an insight as to where the problems lie and the areas which are under the working scope for better productivity. The usage of model clearly depicts the systems and their interrelation among each other. From the result obtained, the availability is decreasing which is not desirable for increasing the productivity of a production unit and hence it should be focused upon. Also, MTBF is increasing which leads to low productivity. Hence, this analysis provides a pathway for further work in order to minimize the under performance of the whole production unit.

9. Acknowledgement

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