Structured Framework for Reliability of an Industrial System Using Fuzzy Approach

Mohd Salman Khan1, Saurabh Jha P2

1,2Amity University, Department of Mechanical and Automation Engineering, Noida, U.P, India

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, Zafiropolous 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 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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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. Volkankovski 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 Lambda-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 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 \( f_A(x) \) is given by

\[
\begin{align*}
&f_A(x) = \\
&\begin{cases}
(x - a)/(b - a), & a \leq x \leq b, \\
1, & b \leq x \leq c, \\
(x - c)(c - d), & c \leq x \leq d, \\
0, & \text{otherwise},
\end{cases}
\end{align*}
\]

It is obvious that in \( f_A^u(x) = (X - a)/ (b - a) \), and \( f_A^l(x) = (X - c)/ (c - d) \). The inverse functions of \( f_A^u(x) \) and \( f_A^l(x) \) are \( g_A^u(y) = a + (b - a)y \) and \( g_A^l(y) = c + (c - d)y \), where \( y \in [0, 1] \).

3.4 Ranking generalized fuzzy numbers with trapezoidal membership functions

Chen 1985 proposed that there are \( n \) generalized fuzzy numbers \( A_1, A_2, ... A_n \) 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

\[
\begin{align*}
&f_{A_i}(X) = \\
&\begin{cases}
wi, & a_i \leq x \leq b_i, \\
w_i(x - c_i)/(a_i - c_i), & c_i \leq x \leq b_i, \\
w_i(x - d_i)/(b_i - d_i), & b_i \leq x \leq d_i, \\
0, & \text{otherwise},
\end{cases}
\end{align*}
\]

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

\[
\begin{align*}
&F_M(x) = \\
&\begin{cases}
W[(x-x_{\min})(x_{\max}-x_{\min})^2], & x_{\min} \leq x \leq x_{\max} \\
0, & \text{otherwise},
\end{cases}
\end{align*}
\]

And

\[
\begin{align*}
&D_G(x) = \\
&\begin{cases}
W[(x-x_{\max})(x_{\max}-x_{\min})^2], & x_{\max} \leq x \leq x_{\min} \\
0, & \text{otherwise},
\end{cases}
\end{align*}
\]
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 cramped 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. Sloting 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 from 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

\[
\lambda^{(\alpha)} = \left[ \prod_{j=1}^{n} ((\lambda_j - \lambda_1)\alpha + \lambda_1) \sum_{j=1}^{n} \left[ (\tau_j - \tau_1)\alpha + \tau_1 \right] \prod_{j=1}^{m} ((\lambda_j - \lambda_2)\alpha + \lambda_2) \sum_{j=1}^{m} \left[ (\tau_j - \tau_2)\alpha + \tau_2 \right] \right]
\]

\[
\tau^{(\alpha)} = \left[ \prod_{j=1}^{n} (\tau_j - \tau_1)\alpha + \tau_1 \right] \sum_{j=1}^{n} \left[ (\tau_j - \tau_1)\alpha + \tau_1 \right] \prod_{j=1}^{m} (\tau_j - \tau_2)\alpha + \tau_2 \right] \sum_{j=1}^{m} \left[ (\tau_j - \tau_2)\alpha + \tau_2 \right] \right]
\]

Expressions for OR transitions

\[
\lambda^{(\alpha)} = \left[ \prod_{j=1}^{n} ((\lambda_j - \lambda_1)\alpha + \lambda_1) + \sum_{j=1}^{n} (\lambda_j - \lambda_2)\alpha + \lambda_2 \right] \left[ \prod_{j=1}^{m} ((\lambda_j - \lambda_1)\alpha + \lambda_1) + \sum_{j=1}^{m} (\lambda_j - \lambda_2)\alpha + \lambda_2 \right]
\]

\[
\tau^{(\alpha)} = \left[ \prod_{j=1}^{n} (\tau_j - \tau_1)\alpha + \tau_1 \right] + \sum_{j=1}^{n} (\tau_j - \tau_1)\alpha + \tau_1 \right] \prod_{j=1}^{m} (\tau_j - \tau_2)\alpha + \tau_2 \right] + \sum_{j=1}^{m} (\tau_j - \tau_2)\alpha + \tau_2 \right] \right]
\]
### 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.

![Integrated framework (working model)](image)

**Figure 2: Integrated framework (working model)**

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### Some basic expressions for fuzzy methodology

<table>
<thead>
<tr>
<th>Gate</th>
<th>( \lambda_{\text{AND}} )</th>
<th>( \tau_{\text{AND}} )</th>
<th>( \lambda_{\text{OR}} )</th>
<th>( \tau_{\text{OR}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \prod_{i=1}^{n} \lambda_{i} )</td>
<td>( \sum_{i=1}^{n} \tau_{i} )</td>
<td>( \prod_{i=1}^{n} \lambda_{i} )</td>
<td>( \sum_{i=1}^{n} \tau_{i} )</td>
<td></td>
</tr>
</tbody>
</table>

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  DOI: 10.21275/ART20171064

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* 1523
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 Crisp 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>
<thead>
<tr>
<th>Machines</th>
<th>Failure rate ($\lambda_i$) failure/hrs</th>
<th>Repair time ($\tau_i$) hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lathe (i=1)</td>
<td>$3.52 \times 10^{-4}$</td>
<td>3</td>
</tr>
<tr>
<td>Lathe (i=2)</td>
<td>$3.52 \times 10^{-4}$</td>
<td>1</td>
</tr>
<tr>
<td>Lathe (i=3)</td>
<td>$2.88 \times 10^{-4}$</td>
<td>2</td>
</tr>
<tr>
<td>Vertical boring machine (i=4,5)</td>
<td>$2.24 \times 10^{-4}$</td>
<td>1</td>
</tr>
<tr>
<td>Tapping machine (i=6)</td>
<td>$3.84 \times 10^{-4}$</td>
<td>1</td>
</tr>
<tr>
<td>Radial drilling machine (i=7,8,9,10)</td>
<td>$2.88 \times 10^{-4}$</td>
<td>1</td>
</tr>
<tr>
<td>Slotter machine (i=11)</td>
<td>$2.24 \times 10^{-4}$</td>
<td>2</td>
</tr>
<tr>
<td>Vertical lathe machine (i=12,13)</td>
<td>$1.60 \times 10^{-4}$</td>
<td>1</td>
</tr>
</tbody>
</table>
6. Reliability Evaluation

Table 2: Reliability Expression

<table>
<thead>
<tr>
<th>Reliability Parameters</th>
<th>Expressions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean time between failures</td>
<td>$\frac{1}{\lambda_1}$</td>
</tr>
<tr>
<td>Mean time to Repair</td>
<td>$\frac{1}{\mu_3}$</td>
</tr>
</tbody>
</table>

Table 3: 15% Left side spread

<table>
<thead>
<tr>
<th>Dof</th>
<th>Failure Rate</th>
<th>Repair Time</th>
<th>Availability</th>
<th>Unavailability</th>
<th>Reliability</th>
<th>Unreliability</th>
<th>MTBF</th>
<th>ENOF</th>
</tr>
</thead>
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<tr>
<td>1</td>
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<td>1.22573277</td>
<td>0.99878543</td>
<td>0.000214573</td>
<td>0.96109307</td>
<td>0.03890693</td>
<td>1009.1879</td>
<td>0.0396373</td>
</tr>
<tr>
<td>0.9</td>
<td>0.000976896</td>
<td>1.20768377</td>
<td>0.99882161</td>
<td>0.001178392</td>
<td>0.9617775</td>
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<tr>
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</table>

Table 4: 15% Right side spread

<table>
<thead>
<tr>
<th>Dof</th>
<th>Failure Rate</th>
<th>Repair Time</th>
<th>Availability</th>
<th>Unavailability</th>
<th>Reliability</th>
<th>Unreliability</th>
<th>MTBF</th>
<th>ENOF</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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</table>

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

$$\lambda = \lambda_1 \lambda_2 \lambda_3 \left( t_{12} + t_{23} + t_{13} \right) R \lambda_5 \lambda_5$$

Later on, a comparison is drawn out amongst these for the behavioral analysis of the systems in the production unit.

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 5: Defuzzification at different spreads

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Crisp value</th>
<th>At 15%</th>
<th>At 25%</th>
<th>At 60%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure rate</td>
<td>0.000992101</td>
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<td>0.000991785</td>
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<td>Repair Time</td>
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<td>Reliability</td>
<td>0.961093068</td>
<td>0.961093791</td>
<td>0.961121337</td>
<td>0.96115064</td>
</tr>
<tr>
<td>Unreliability</td>
<td>0.038906932</td>
<td>0.038906208</td>
<td>0.038887663</td>
<td>0.03884936</td>
</tr>
<tr>
<td>MTBF</td>
<td>1009.187883</td>
<td>1012.544959</td>
<td>1013.274859</td>
<td>1010.7340315</td>
</tr>
<tr>
<td>ENOF</td>
<td>0.039637306</td>
<td>0.039629683</td>
<td>0.039623471</td>
<td>0.039612298</td>
</tr>
</tbody>
</table>

Table 6: Change in Defuzzification at different spread

<table>
<thead>
<tr>
<th>Trend</th>
<th>-6.48977E-05</th>
<th>-0.000253346</th>
<th>-0.000131762</th>
<th>decreasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.000389267</td>
<td>-0.000458088</td>
<td>-0.012632278</td>
<td>decreasing</td>
<td></td>
</tr>
<tr>
<td>-3.67307E-06</td>
<td>-6.33252E-06</td>
<td>-0.00012523</td>
<td>decreasing</td>
<td></td>
</tr>
<tr>
<td>0.002975394</td>
<td>0.005200811</td>
<td>0.092663205</td>
<td>increasing</td>
<td></td>
</tr>
<tr>
<td>7.524356E-07</td>
<td>1.9296E-05</td>
<td>3.9851E-05</td>
<td>increasing</td>
<td></td>
</tr>
<tr>
<td>-1.86151E-05</td>
<td>-0.000476874</td>
<td>-0.00095942</td>
<td>decreasing</td>
<td></td>
</tr>
<tr>
<td>0.003315483</td>
<td>0.005200811</td>
<td>0.092663205</td>
<td>increasing</td>
<td></td>
</tr>
<tr>
<td>-0.000192346</td>
<td>-0.000156771</td>
<td>-0.000282058</td>
<td>decreasing</td>
<td></td>
</tr>
</tbody>
</table>

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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References