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Safety Risk Assessment; Using Fuzzy Failure Mode and Effect Analysis and Fault Tree Analysis

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Abstract. The failure mode and effects analysis (FMEA) is a qualitative, Inductive and effective method for detecting errors, faults, and failures in a system and fuzzy logic can improve that technique with more logical outputs. Moreover, the fault tree analysis (FTA) as a probabilistic risk assessment method is among the effective technique for calculating the probability of errors, faults, failures, reliability and safety integrity level (SIL) verification resulting in certain events at higher levels. The FTA also detects the main causes of events in complicated systems. Although this technique appears to be time-consuming in systems with many diverse components, it is considered a powerful tool. In this paper, the fuzzy FMEA analyzes the failure modes in a hypothetical system. After that, the process with the highest risk is selected as the input of an FTA. According to the qualitative and quantitative analysis of FTAs, a series of corrective actions will be proposed to reduce the failure probability.

AMS Subject Classification 2020: 03B52, 03E72, 68T27
Keywords and Phrases: Fault Tree Analysis (FTA), Failure Mode and Effect Analysis (FMEA), Qualitative Risk Assessment, Probabilistic Risk Assessment (PRA), Fuzzy Number.

1 Introduction

Various methods, including quantitative and qualitative, have been proposed to assess the risk. FMEA represent a preventative method with a teamwork approach. FMEA was first developed as a design methodology in the aerospace industry for needs related to reliability and safety. And then more widely, used in industry, to ensure product safety and reliability. This tool is one of the effective models for fault prediction and finding the most economical solution to prevent faults. FMEA is a structured way to start designing or reviewing and developing the product or service design in an organization [12]. FMEA mainly prevents the occurrence of faults, helps in creating and developing products, processes or serious services and records parameters and indicators in the design and development process or service [3]. FMEA results are in response to the following questions: What are the faults, bugs, or hazards? Which identified faults, bugs, or hazards are of greater importance (risk)? What are the possible solutions which could be done to reduce the occurrence of these situations? The FMEA acts systematically to answer these questions in the best way and, using the knowledge and expertise of a working group, prioritizes them in addition to identifying faults and problems or hazards at the heart of the operation.

Another comprehensive method of its kind is FTA. This method was first developed in 1961-62 in Bell Telephone Laboratories and then developed by Watson to determine and improve the reliability of the intercontinental ballistic missile control system. This method was developed by Boeing Airlines in the following

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years and became legal. Since 1965, the use of the FTA method has spread to various industries such as aerospace, nuclear, chemical, etc., and it has been widely used to analyze the reliability and safety of systems [8].

FTA is an analytical technique that identifies system malfunctions, and by providing a quantitative analysis of the system, all possible paths to system malfunctions will be identified. FTA is a graphical model, which shows the sequence of events of a fault. In fact, the fault tree shows how failure occurs by introducing logical connections to events. Consider that, as the input to the fault tree analysis in the problem recognition stage, the fault mode selected in the FMEA for investigation or has a higher risk can be used. For example, items whose risk priority number is known to be higher than the allowable level, or items that have been identified in the FMEA area chart analyzed as items to review and determine corrective action, could be the input of FTA. In this article, by using a hypothetical process, the corrective action priorities are identified by the FMEA method, and the highest risk is used as the input of an FTA. In this article, the faults scenarios in FMEA are prioritized by the FRPN method, which due to the characteristics of fuzzy logic, the use of FRPN has a higher priority than RPN.

In general, FTA is a powerful analogical tool for batch analysis of a system's events. This technique is mainly used for evaluating complex systems. Today, a variety of computer programs have been developed to create the logical structure and perform the necessary calculations. The method creates connections between system events by means of logical symbols that represent the effects of an accident or hazard. The technique is robust and convenient for situations that have traditionally been decomposed in series or in parallel. This model is also used for dynamic cases, which performs qualitative and quantitative analysis and allows the analyzer to evaluate different alternatives in system design and the fault range, reduction time, measure repair and failure times and other dynamic system operations.

Fault tree analysis is very suitable in complex processes with a large variety of components and parts and leads to useful results. Although this method qualitatively evaluates a predetermined risk and adverse event, it can be quantitatively analyzed to obtain interesting and documented results and provide a solution for management decisions to be able to allocate resources and energy more confidently and ensure the system against possible damages by highlighting the safety of the system [4].

2 Literature Review

Akyildiz and Mentes (2017) used fuzzy AHP and fuzzy TOPSIS methods to assess the risks of cargo vessel accidents [1]. Khodadadi-Karimvand and Shirouyehzad (2021) use FMEA as a risk identification tool. Then, the Fuzzy Risk Priority Number (FRPN) is calculated and triangular-fuzzy numbers are prioritized through Fuzzy TOPSIS [7]. FMEA is an engineering technique that is used to identify the existing or potential failures or problems in a design, process, or service structure of a system before they occur, to prevent undesirable incidents and protect employees from occupational accidents and diseases by taking the necessary measures [13]. The severity and types of potential failures in the analyzed system are identified by FMEA, which allows decision makers to take the necessary risk-reducing measures [5].

FTA should be conducted by a team of experts on the scope to be analyzed. The method examines the causes of incidents and the conditions triggering the incident. The analysis includes the equipment and components used by the employee while performing the work, together with the components and system conditions [6].

FTA is a deduction analysis method that allows identifying and analyzing the potential causes, conditions, and factors that contribute to the occurrence of an unidentified, undesirable major incident. FTA method is used to analyze, assess, and graphically illustrate the hierarchical flow of potential incidents or situations that may negatively affect the system reliability and usability [9].

Many studies have been conducted using both FTA and FMEA methods. Li and Gao (2010) pointed out the necessity to identify the potential root causes in the system and analyze the critical situation in order to determine the maintenance operations required based on the reliability-centered maintenance and radical maintenance approaches using the FTA and failure mode effect and criticality analysis (FMECA) methods. In addition, the FTA approach is adopted to evaluate the reliability of systems and analyze the probability of failure occurrence [2].

Barozzi et al. in the paper, a representative biogas production plant was considered, and a risk assessment was carried out through the combination of Recursive Operability Analysis and Failure Mode and Effects Criticality Analysis (FMECA). The methodology is rigorous and allows for both the identification and the quantification of accidental scenarios due to procedural errors and equipment failures, which miss in the literature for the case of biogas. The analysis allows the automatic generation of the Fault Trees (FTA) for the identified Top Events, which can be numerically solved [11].

3 Methodology

In order to create a model for calculating the degree of risk priority and prioritizing faults and their effects using fuzzy logic, the following three main steps must be followed:

- Select fuzzy membership function
- Form a membership function by multiplying the membership functions by severity, probability, detection.
- De-fuzzy membership function
- Quantitative and qualitative analysis of the fault tree for the highest risk obtained

In this article, a hypothetical system with four modes of faults, failure and lost is analyzed and the highest risk calculated in the Fuzzy FMEA input of a fault tree analysis is placed.

3.1 Selection of Fuzzy Membership Function

For all the affective factors in the risk-taking degree, such as severity, probability and detection, five linguistic variables can be used VL, L, M, H and VH. Where 5 linguistic variables are assigned to rank according to table 1 [7].

Table 1: Fuzzy Numbers of Linguistic Variables Corresponding to Ranks 1 to 10

Fuzzy Number	Verbal Variable	Rank
(0.9,1,1)	VH	9,10
(0.7,0.85,1)	H	7,8,9,10
(0.4,0.6,0.8)	M	4,5,6,7,8
(0.2,0.35,0.5)	L	2,3,4,5
(0,0.15,0.3)	VL	1,2,3

$\{VL, L, M, H, VH\} = T(x) =$ Set of Linguistic Variables Values
$[0, 1] = U =$ Variation Amplitude of the Reference Set
Performing calculations with fuzzy numbers is very complex due to their special structure. To facilitate and apply fuzzy numbers, special fuzzy numbers are used in calculations. These special numbers are bell-shaped, triangular, trapezoidal, L-R trapezoidal, L-R triangular. In this paper, triangular fuzzy numbers are used.

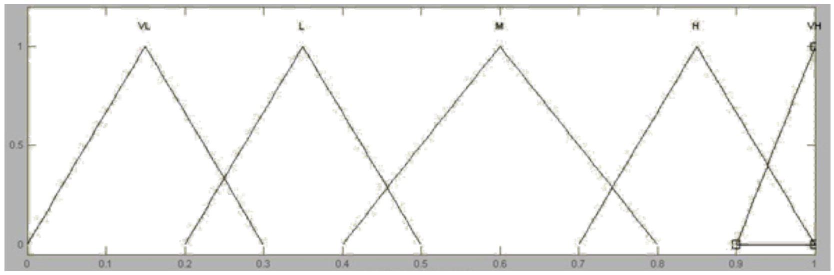

Figure 1: Membership Function of Linguistic Variables

3.2 Forming a Membership Function by Multiplying the Membership Functions of Severity, Occurrence and Detection

FRPN is calculated from the following relation by multiplying the membership functions of severity, probability and detection. If M is a linguistic variable, its triangular fuzzy number may be defined as follows [14]:

$$M = (l, m, u)$$

Where u, l and m are the upper limit, the lower limit and the mean of u, respectively where the membership degree of l is 1.
Algebraic operations rules are applied on triangular numbers as follows to calculate RPN:
RPN = Severity × Occurrence × Detection
FRPN $=(l_1, m_1, u_1) \times (l_2, m_2, u_2) \times (l_3, m_3, u_3) = (l_1 l_2 l_3, m_1 m_2 m_3, u_1 u_2 u_3)$

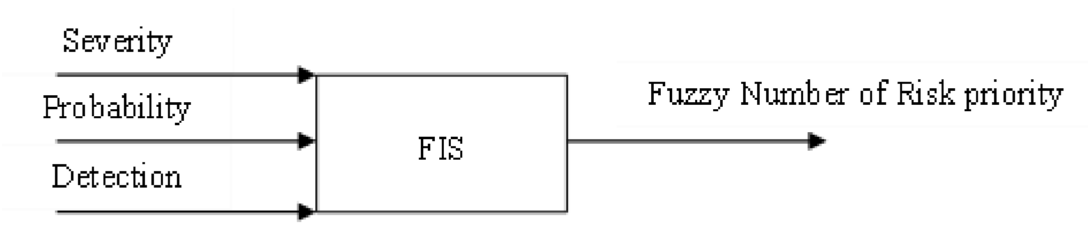

Figure 2: FRPN Model

3.3 Defuzzification

There are several ways to convert a fuzzy number to an exact value. In this paper, the values obtained from the formation of the membership function multiplied by the membership functions of severity, probability, detection using the left and right scoring method of fuzzy, non-fuzzy numbers [15].

After determining the linguistic variables instead of the values severity, probability, detection for the three potential fault modes, we replace the fuzzy values according to the Table 2.

Then, according to Table 3, the fuzzy RPN values are converted to a non-fuzzy number using the left and right scoring method, or the definite RPN resulting from de-fuzzy.

Table 2: Membership Function for the Severity, Probability and Detection

Severity	Probability	Detection	Failure Modes	#
(0.7, 0.85, 1)	(0, 0.15, 0.3)	(0.2, 0.35, 0.5)	Failure 1	1
(0.7, 0.85, 1)	(0.4, 0.6, 0.8)	(0.2, 0.35, 0.5)	Failure 2	2
(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0, 0.15, 0.3)	Failure 3	3
(0.7, 0.85, 1)	(0.7, 0.85, 1)	(0, 0.15, 0.3)	Failure 4	4

Table 3: Defuzzification Using the Left and Right Scores

Total Score	Left Side Score	Right Side Score	FRPN	#
0.0517	0.9554	0.0587	(0, 0.0446, 0.15)	1
0.1877	0.9489	0.3243	(0.056, 0.1785, 0.4)	2
0.1302	0.9460	0.2064	(0, 0.054, 0.192)	3
0.1096	0.8917	0.1110	(0, 0.1083, 0.3)	4

3.4 Fault Tree Analysis

After determining the risk of activities using the FMEA method, we analyze the state of fault, failure and breakage, which has the highest risk, using the FTA method and during the following steps.

A: System definition

B: Fault tree formation

C: Qualitative analysis

D: Quantitative analysis [4].

3.5 Define the System as a Fault Tree

This includes the scope of the analysis including defining what is considered a failure. This becomes important when a system may have an element fail or a single function fails and the remainder of the system still operates. The highest risk faults, failure and failure modes are considered as the top event and the sub-events $G1, G2$ and $G3$ are on one level and the basic events $E1, E2, E3$ and $E4$ are on the next level. In fact, intermediate or sub-events and basic events are the causes of the top event that have been identified.

3.6 Fault Tree Formation

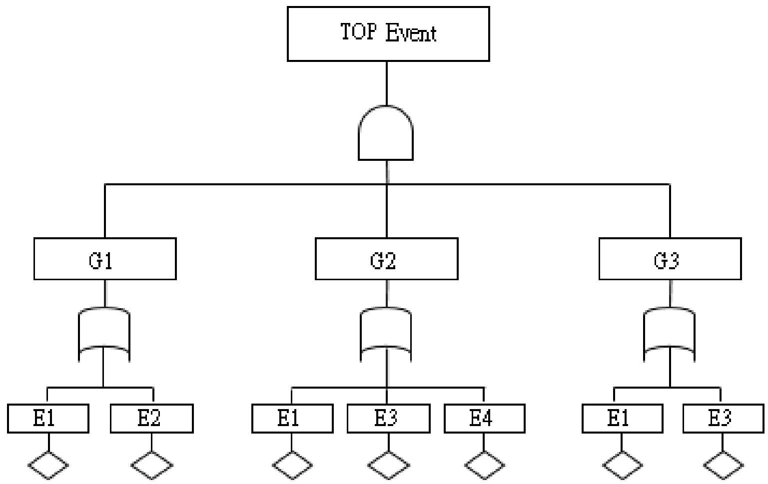

Figure 3: Drawn Fault Tree

3.7 Qualitative Analysis

Fault tree analysis is done in two stages, the first stage is qualitative analysis, which we will discuss very briefly. Qualitative analysis refers to the preparation of various combinations of events that cause system failure. In other words, in this section, the goal is to determine the minimum cut sets for the final fault tree incident.
In this fault tree the minimum cut sets are:

$$M\ cs1 = E1$$

$$M\ cs2 = E2, E3$$

Minimal cut set No. 1 is more important because of the lower floor and the importance of all events is as follows: [10]

$$E1 > E3 > E2 > E4$$

3.8 Quantitative Analysis

For a quantitative analysis, we need a list of equipment or parts in which sub-events occur due to adverse conditions and cause the process to fail.
Here we assume the equipment or part according to Table 4 and in front of this equipment we obtain the failure rate in a specified period of time using statistics and records and reports and repair instructions of the devices and then calculate the probability of failure by using the failure rate and finally, calculate the probability of process failure. In this case study, we examine the performance of equipment at 1,200 hours over 5 years.

Before calculating the probability, using Boolean Algebra, we express a method that can be used to calculate the failure rate and probability for equipment and parts. The diagram in Figure 2, which is more commonly used in maintenance topics and is known as the Bathtub Hazard Rate Curve, is divided into three sections:

Table 4: Failure Rate and Probability

Probability	Failure Rate	Symbol	Equipment
0.0004	1	$E1$	No. 1
0.0000	0	$E2$	No. 2
0.0004	1	$E3$	No. 3
0.0000	0	$E4$	No. 4

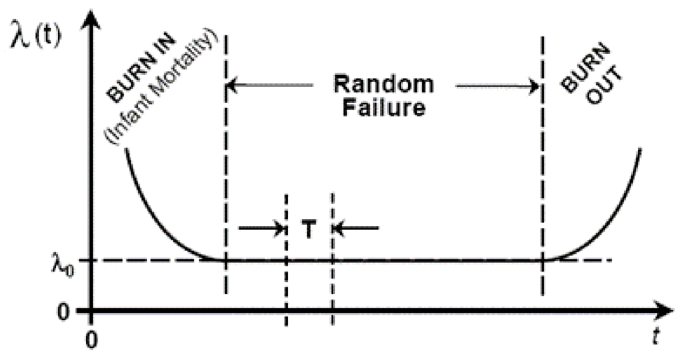

Figure 4: Bathtub Failure Rate Curve

The first section is related to the initiation of the system. At this time, the probability of failure of the system is high and during this area, the failure rate decreases with increasing time. In the second time interval, the average failure per unit time is almost constant, and failures occur randomly and unpredictably, which can have a variety of reasons, and in the third section, the device wears out and runs out. The working period is approaching and the probability of failure is high and during this area the failure rate increases with increasing time. If $\lambda(t)$ is constant, it can be shown that the probability distribution function of the random variable at the time of the failure event is an exponent with the parameter λ. Most of the time and during the operation of the system, the value of $\lambda(t)$ is independent of time and is constant. This means that failure can occur independently and accidentally at any time interval from the working area of the device. In this case we will have:

$$\lambda(t) = \lambda = etc.$$

Now with having $\lambda(t)$ and putting it in the Exponential Distribution function we have:

$$P_F = 1 - e^{-\lambda t}$$

Where P_F is the probability of failure and t is the time in the subject which we are discussing about at the failure rate [10].

3.9 Calculation of Probability and Failure Rate

$G1 = E1 + E2 = 0.0004 + 0.0000 = 0.0004$

$G2 = E1 + E3 + E4 = 0.0004 + 0.0004 + 0.0000 = 0.0008$

$G3 = E1 + E3 = 0.0004 + 0.0004 = 0.0008$

Probability of process failure $= G1 + G2 + G3 = 0.0004 + 0.0008 + 0.0008 = 0.0020$
Now, using the probability of process failure, we calculate the failure rate:

$$P_F = 1 - e^{-\lambda t}$$

$$0.0020 = 1 - e^{-\lambda t} \Longrightarrow -\lambda t = Ln(1 - 0.0020) \Longrightarrow \lambda t = 0.002002002$$

According to the 5 years time period, we have:

$$\lambda = \frac{0.002002002 \times 1200}{5} = 0.4804864$$

The above value is the number of failures per a unit year. That is, almost every two years, there is a possibility of failure once.

4 Conclusion

After the results, an expert team from all relevant groups should try to reduce or eliminate the severity of adverse events and provide suggestions. Finally, it is necessary to mention that today in all industries, resource and energy management and the right decision to allocate them to achieve full productivity, is the main concern of managers. Fault and failure state analysis and fault tree analysis are each efficient tools and due to the time-consuming method of fault tree analysis to investigate the undesirable states of the system, it seems that if the output or outputs of the analysis method and to put the breakdown and failure analysis into the input of a fault tree, we have taken steps to reduce or eliminate adverse events by considering the time and costs involved.

As it turns out, fuzzy logic in risk assessment gives us a more logical output, but in any case, outputs of the normal or fuzzy failure mode and effects analysis technique and other qualitative and Inductive methods such as Hazard and Operability Analysis (HAZOP), Hazard Identification (HAZID), Hazard Analysis (HAZAN), etc. can use as input of a fault tree analysis and other probabilistic risk assessment (PRA) or quantitative risk assessment (QRA) methods.

Conflict of Interest: The authors declare that there are no conflict of interest.

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