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# Fuzzy Fault Tree Analysis of the Marine Diesel Engine Jacket Water Cooling System

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**Abstract:** This article presents a case study of fuzzy Fault Tree Analysis (FTA) method application to study of the reliability of Jacket cooling water system of a marine diesel engine. Due to the uncontrollable working conditions such as ship mobility, states of loading and weather conditions, it is difficult to get the exact value of failure probability of the basic components including in the system. To overcome the over and under estimation of the failure probability of basic events as well as the probability of the undesired event of FTA, fuzzy set theory is applied in FTA. Fuzzy failure rate of the system is calculated by fuzzy numbers and fuzzy operators. The result of the FTA is given by fuzzy probability which can compensate the vagueness or uncertainty of probability of basic events and engineering errors. Not only the reliability of the jacket water cooling system but also the importance measure of the basic events of cooling system are analyzed by fuzzy FTA method. Fuzzy probability ranking method and Graded Mean Integration Representation (GMIR) distance method are proposed to use in calculation of the fuzzy importance measures of the components of the system. From this study, it can be concluded that the jacket water cooling system analyzed is highly reliable and the basic event of the failure of the supply air is the most critically important component in the major of events in the system.

**Key words:** Reliability, fault tree, fuzzy probability, fuzzy number, cooling system, reliability importance measure

## INTRODUCTION

All power generating machine such as internal combustion engine, gas turbines and nuclear reactors need efficient cooling system for safe and smooth operation of the system. The disaster of the explosion of Fukushima Nuclear Reactors in Japan was caused by breakdown of cooling system in earthquake and tsunami.

For long term running and safe operation of on board diesel engine, the cooling system is the most important supporting system of the operation of engine. Cooling systems and temperature control systems are important to maintain the temperature of engine at most favorable level of energy efficiency and to ensure the long life of the parts using in diesel engine. On board there are two main types of cooling system, one is sea water cooling system and the other is fresh water cooling system also known as central cooling water system. Fresh water central cooling system can be further divided into low temperature fresh water cooling system and high temperature fresh water cooling system. Jacket water cooling system is a high temperature fresh water cooling system and the safe and smooth operation of this system is based on the operation conditions of both sea water and fresh water cooling system (Zhou and Xu, 2011; McGeorge, 2002).

To obtain high reliable water cooling system, failure analysis of the cooling systems is carried out by using different reliability analysis methods from design stage to operation stage. In doing these kinds of analysis, the most challenging problem for engineers is to get the exact value of failure probability of the basic components (basic events). The failure probability of basic components (basic events) and the reliability of the cooling system depends on factors such as ship mobility, states of loading and weather conditions. In this study, Fault Tree analysis is used to make qualitative analysis of the system and Fuzzy probability is used for assigning the failure probability of basic events of FTA to overcome the over and under estimation and to get more reliable and reasonable results in quantitative analysis of the system. Fuzzy probability is used to determine the fuzzy failure rate of the basic events based on the statistical data, influencing factors and expert judgments. Fuzzy Fault Tree Analysis (FFTA) is used to find out the fuzzy

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probability of the occurrence of the most undesired events of the system and fuzzy important index is used to discover the critical components of the system which can lead to major undesired events of the system (Tanaka *et al*., 1983). This study presents in 6 parts (1) Fault tree analysis (2) Fuzzy numbers and its operation (3) Fuzzy operations for gates of FTA (4) Calculation of Fuzzy important measure (5) Reliability analysis of the jacket water cooling system (6) Result and discussion and (7) Conclusion.

**Overview of the method of study:** The study can be divided into two major parts, the first one describes about the theory and method of study (from part 1-5) and the second one describes about the results and discussions of the study (from part 6-7). The first part presents about the theory of fault tree analysis and applying of fuzzy probability in fault tree analysis, detail of the type of fuzzy number used in this study and their operations are shown in part two. Part three describes about how to calculate the outcomes of logic gates in FTA by using fuzzy failure probability. Fuzzy probability ranking method and Graded Mean Integration Representation (GMIR) distance method which are proposed to use in calculation of the fuzzy importance measures of the components of the system are explained in part four. The reliability study of marine diesel engine jacket water cooling system is widely discussed with three separate sections in part five. The first section describes about the operation of jacket water cooling system, the second section discusses about the obtaining of fuzzy failure probability of components used in the system and the third section explains about the procedure of fuzzy fault tree calculation for the top undesired event (failure to maintain desired temperature of jacket cooling water system). And the results, fuzzy failure probability of jacket water cooling system and fuzzy important measures of the components of the system which are calculated by two different methods mentioned in part four, are described in the section of results and discussions (part 6). Finally the study is concluded by recommending how this study can be dealt with two major aspects in reliability analysis of any onboard system and reveals the most critical and least critical components of the diesel engine jacket water cooling system.

## FAULT TREE ANALYSIS

Fault Tree Analysis (FTA) is a powerful method to calculate the probability of the undesired outcomes of a system at the same time it can calculate how importance of the basic events causing the major undesired events (Vesely *et al*., 1981). Based on the combination of different failure causes such as hardware failure, common cause failure, environmental impact and human error, the probability of the undesired outcome is calculated (Yuhua and Datao, 2005). Logic gates are used as nodes in combination of basic events which can give middle events and then up to reach the target undesired top event. OR gate AND gate and NOT gate are the most common static gates used by FTA as well as in Fuzzy FTA (FFTA). Although, FTA users can easily understand and clearly find out the causes of top undesired events from FTA systematic diagram, FTA has weak points in solving problems with uncertain failure rates of basic events. To overcome these problem researchers combined Fuzzy concept to FTA and invented Fuzzy Fault Tree Analysis (FFTA) method to solve the problem of uncertain failure rates of basic events (Mentes and Helvacioglu, 2011; Ma *et al*., 2011; Wang *et al*., 2011). This study used the integrated concept of FFTA to calculate the fuzzy probability of undesired major event.

## FUZZY NUMBER

Fuzzy probability is a fuzzy number which is expressed by a fuzzy set (Huang *et al*., 2001) and characterized by its membership function μ. Let $\tilde{A}\in(-\infty, +\infty)$. Tanaka *et al*. (1983) described about the L-R fuzzy number, suppose L and R as referring functions of the fuzzy numbers. If:

$$\mu_{\tilde{A}}(x) = \begin{cases} L\dfrac{(m-x)}{\alpha} \\ R\dfrac{(x-m)}{\beta} \end{cases} \text{where} \begin{cases} x \le m, \alpha > 0 \\ x > m, \beta > 0 \end{cases} \quad (1)$$

then $\tilde{A}$ is called L-R fuzzy number. The parameter m is the mean of the fuzzy number $\tilde{A}$ and α, β is the left and right expansion of $\tilde{A}$ which can be represented as $\tilde{A} = (m, \alpha, \beta)_{LR}$. The membership function of $\tilde{A}$ is equal to zero when $x \le m-\alpha$ or $x \ge m+\beta$ that means if x is out of the range of (m-α, m+β), it does not belong to $\tilde{A}$.

Fuzzy probability can be represented by a triangular or trapezoidal shape or bell shaped membership function. Generally triangular and trapezoidal membership functions are widely used to represent the failure nature of equipments. Triangular membership functions are used to represent more or less probability estimation of failure occurrence (e.g., the probability of failure occurrence is about 0.0001) and a trapezoidal membership function is better to used in describing failure probability interval of equipments (e.g., the probability of failure occurrence lies between 0.00001 and 0.000025). Due to the failure nature of cooling system equipments, triangular fuzzy number will be used in further calculations of this study. Details properties and calculation of triangular fuzzy number will discuss in following sections.

**Triangular fuzzy number:** A fuzzy number $\tilde{A}$ is termed as triangular fuzzy number if the membership function of fuzzy number $\tilde{A}$ is defined by the following Eq. 2. A triplet (a, m, b) or $\tilde{A}$ = (m-a, m, b-m) can be represented the triangular fuzzy number. The left and right expansions of triangular fuzzy number and the confidence level of probability of uncertain events can be obtained from statistical data and expert judgment of the system:

$$\mu_{\tilde{A}}(x) = \begin{cases} 0 & (x < a) \\ \dfrac{x-a}{m-a} & (a \le x \le m) \\ \dfrac{b-x}{b-m} & (m < x \le b) \\ o & (x > b) \end{cases} \tag{2}$$

**Algebraic operation of fuzzy number:** Let $\tilde{G}_1$ and $\tilde{G}_2$ be two fuzzy number $\tilde{G}_1 = (a_1, m_1, b_1)$ and $\tilde{G}_2 = (a_2, m_2, b_2)$. The basic arithmetic operations of two fuzzy numbers are shown in Eq. 3-4 and operation between crisp number and fuzzy number is shown by Eq. 5:

$$\tilde{G}_1 + \tilde{G}_2 = (a_1 + a_2, m_1 + m_2, b_1 + b_2) \tag{3}$$

$$\tilde{G}_1 - \tilde{G}_2 = (a_1 - a_2, m_1 - m_2, b_1 - b_2) \tag{4}$$

$$1 - \tilde{G}_1 = (1 - a_1, 1 - m_1, 1 - b_1) \tag{5}$$

In multiplication of two triangular fuzzy numbers, the following Eq. 6 is used instead of the real product of two triangular fuzzy numbers which is not a triangular fuzzy number (Mao *et al*., 2010):

$$\tilde{G}_1 \times \tilde{G}_2 = (a_1 \times a_2, m_1 \times m_2, b_1 \times b_2) \tag{6}$$

## FUZZY OPERATORS

Conventional fault tree methods used Boolean operators AND, OR and NOT gates with precise probability of basic events to calculate the probability of top event. If a fuzzy event 'i' is represented by a possibility function $\tilde{G}_i$, fuzzy operators are used to calculate the probability of top event (Ferdous *et al*., 2009). Generalized Fuzzy Boolean NOT operator can be denoted as $\tilde{G}_{not}$ and defined as:

$$\tilde{G}_{not} = 1 - \tilde{G}_1 = 1 - (a_i, m_i, b_i) = (1 - a_i, 1 - m_i, 1 - b_i) \tag{7}$$

In FTA, the result of the AND gate and OR gate operation of the précised probabilities of basic events $G_i$ (where i = 1, 2, 3,..., n) can be represented as:

$$G_{AND} = \prod_{i=1}^{n} G_i \tag{8}$$

$$G_{OR} = 1 - \prod_{i=1}^{n} (1 - G_i) \tag{9}$$

and their fuzzy operations can be represented as:

$$\tilde{G}_{AND} = \prod_{i=1}^{n} \tilde{G}_i = \prod_{i=1}^{n} (a_i, m_i, b_i) = \left( \prod_{i=1}^{n} a_i, \prod_{i=1}^{n} m_i, \prod_{i=1}^{n} b_i \right) \tag{10}$$

$$\begin{aligned} \tilde{G}_{OR} &= 1 - \prod_{i=1}^{n} (1 - \tilde{G}_i) = 1 - \prod_{i=1}^{n} (1 - (a_i, m_i, b_i)) \\ &= 1 - \left( \prod_{i=1}^{n} (1 - a_i), \prod_{i=1}^{n} (1 - m_i), \prod_{i=1}^{n} (1 - b_i) \right) \\ \tilde{G}_{OR} &= \left( 1 - (\prod_{i=1}^{n} (1 - a_i), 1 - \prod_{i=1}^{n} (1 - m_i), 1 - \prod_{i=1}^{n} (1 - b_i) \right) \end{aligned} \tag{11}$$

## FUZZY IMPORTANCE MEASURE

In conventional FTA, there are three kinds of importance measures, Birnbaum importance measure, Criticality importance measure and Fussell-Vesely importance measure, are carried out to know the structural importance, integrated structural and the reliability importance of basic component or event (criticality Importance) and importance of the contribution a basic event in different cut sets. In Fuzzy FTA, fuzzy importance measure of a basic event or component is calculated by measuring the difference between two fuzzy probabilities of the top event of a fault tree with and without existence of that basic event (Tyagi *et al*., 2010).

In this study, two new fuzzy importance measure methods will be introduced and compare the results with each other to verify the results. $\tilde{G}_T$ in Eq. 12 denotes the probability of absolute occurrence of top event and $\tilde{G}_{T_i}$ in Eq. 13 is the probability of occurrence of top event in absence of basic event i. It can be shown as follow:

$$\tilde{G}_{TOP}(\tilde{G}_1,...,\tilde{G}_i,...,\tilde{G}_n)=\tilde{G}_T \quad (12)$$

$$\tilde{G}_{TOP}(\tilde{G}_1,...,\tilde{G}_{i-1},0,\tilde{G}_{i+1},...,\tilde{G}_n)=\tilde{G}_{T_i} \quad (13)$$

The first proposed method of fuzzy important measure can be executed by ranking of fuzzy probability of the top events $\tilde{G}_{T_i}$ by applying the main idea of the ranking of fuzzy number method. Detail of this method is explained in the reference (Thorani *et al*., 2012). First the incentre of the triangular fuzzy number $I_{\tilde{G}_{T_i}}$ can be found by Eq. 14. The rank of the fuzzy probability $R(\tilde{G}_{T_i})$ can be calculated by using Eq. 15:

$$I_{\tilde{A}}(\bar{x}_0,\bar{y}_0)=\left(\frac{x\left(\frac{a+2m}{3}\right)+ym+z\left(\frac{2m+b}{3}\right)}{x+y+z},\frac{x\left(\frac{w}{3}\right)+y\left(\frac{w}{2}\right)+z\left(\frac{w}{3}\right)}{x+y+z}\right) \quad (14)$$

$$R(\tilde{G}_{T_i})=x_0\times y_0=\left(\frac{x\left(\frac{a+2m}{3}\right)+ym+z\left(\frac{2m+b}{3}\right)}{x+y+z}\times\frac{x\left(\frac{w}{3}\right)+y\left(\frac{w}{2}\right)+z\left(\frac{w}{3}\right)}{x+y+z}\right) \quad (15)$$

Where:

$$x=\frac{\sqrt{(2b-2m)^2+w^2}}{6},\ y=\frac{\sqrt{(b-a)^2}}{3},$$
$$z=\frac{\sqrt{(2m-2a)^2+w^2}}{6},\ 0<w\le 1$$

The higher the rank of the fuzzy number the less fuzzy importance measure of the basic event for the system. The second proposed fuzzy important measure of basic events can be evaluated by using fuzzy distance method. First calculate the fuzzy number $(\tilde{G}_T-\tilde{G}_{T_i})$ where i = 1, 2, 3,... for all basic event and find the maximum fuzzy number of $(\tilde{G}_T-\tilde{G}_{T_i})$. Then the fuzzy distance between each fuzzy number $(\tilde{G}_T-\tilde{G}_{T_i})$ and the maximum fuzzy number of $(\tilde{G}_T-\tilde{G}_{T_i})$ are calculated by Graded Mean Integration Representation (GMIR) distance method (Chen and Wang, 2006). GMIR of a triangular fuzzy number $\tilde{G}=(a,m,b)$ can be found as follow:

$$P(\tilde{G})=\frac{a+4m+b}{6} \quad (16)$$

And the distance between two fuzzy numbers can be defined as:

$$\left|P(\tilde{G}_1)-P(\tilde{G}_2)\right| \quad (17)$$

Then the fuzzy important measure can be found by using Eq. 18:

$$FIM=\frac{1}{1+\text{Distance of fuzzy number}\left(\tilde{G}_T-\tilde{G}_{T_i}\right)\ \text{from Max of fuzzy number}\left(\tilde{G}_T-\tilde{G}_{T_i}\right)} \quad (18)$$

## RELIABILITY ANALYSIS OF JACKET WATER COOLING SYSTEM

**System analysis of the jacket water cooling system:** Jacket water cooling system cools the most important working parts of a diesel engine such as cylinder jacket, piston heads, pistons, exhaust valves. Jacket water cooling system locates in the centre of heat exchanging system. The heat from engine is removed by High Temperature fresh water cooler (H.T. F.W), the heat from H.T.F.W cooler is removed by fresh water central cooler and the heat from central cooler is removed by sea water. The detail analysis of sea water cooling system is not included in the scope of reliability analysis of the jacket water cooling system. Components include in this analysis is as shown in Fig. 1. Failure in temperature control of jacket water cooling system is caused by two main factors (1) Primary water cooling system (High Temperature Fresh Water cooling system) and (2) Secondary water cooling system (Low Temperature Fresh Water Cooling system).

Main Engine Jacket water piping, H.T F.W cooler, circulation pumps, automatic control three way valves, temperature sensor and controller, automatic pump controller, H.T F.W high pressure tank, level sensors and water pump are basic components of the primary water cooling system. Central cooler, lube oil cooler, circulations pumps, automatic control three way valves, temperature controller, automatic pump controller, control air supply and temperature sensors are major components of primary fresh water cooling system. Fault tree diagram of the failure of the temperature control of jacket water cooling system is as shown in Fig. 2-3.

**Method of evaluating the fuzzy probability of basic events:** Industrial databases are not product-specific or application-specific; that is, they do not distinguish between harsh or mild environments, process conditions, or levels of maintenance and inspection. If the systems

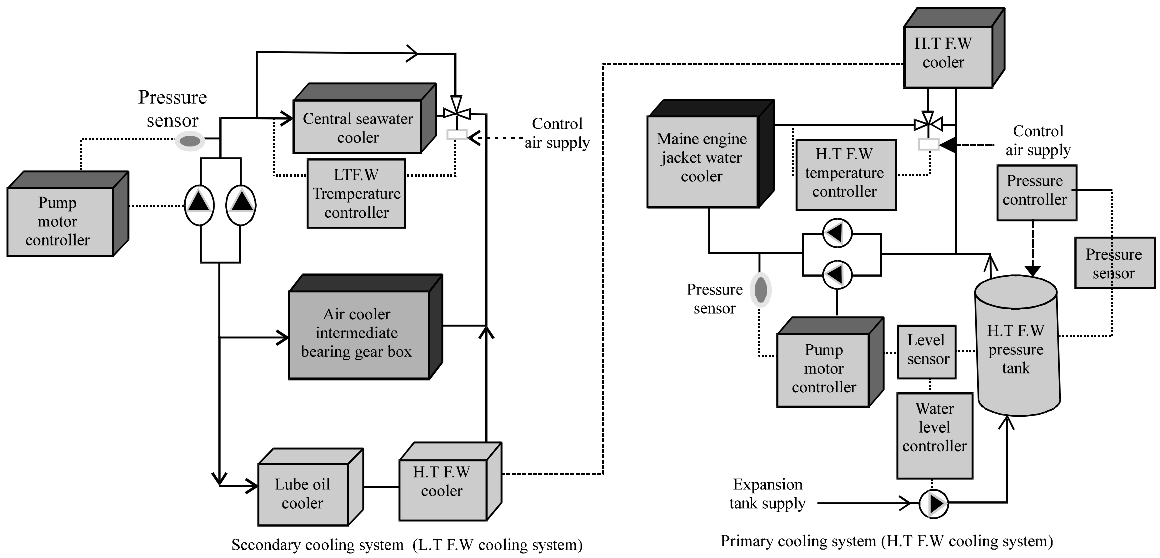



Fig. 1: Components include in the analysis of jacket water cooling system. This figure describe the overview of the central water cooling system or fresh water cooling system using onboard and it also shows the clear boundary between low temperature fresh water cooling system and high temperature fresh water cooling system. Heat from jacket is removed by H.T.F.W cooling system and heat from H.T.F.W is removed by L.T.F.W cooling system and heat from L.T.F.W is removed by sea water cooling system which is not include in this analysis

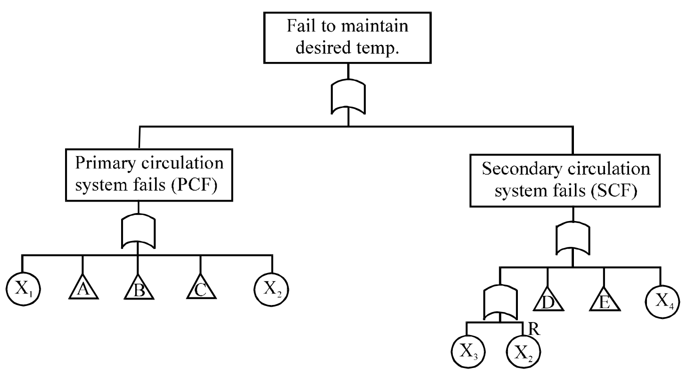
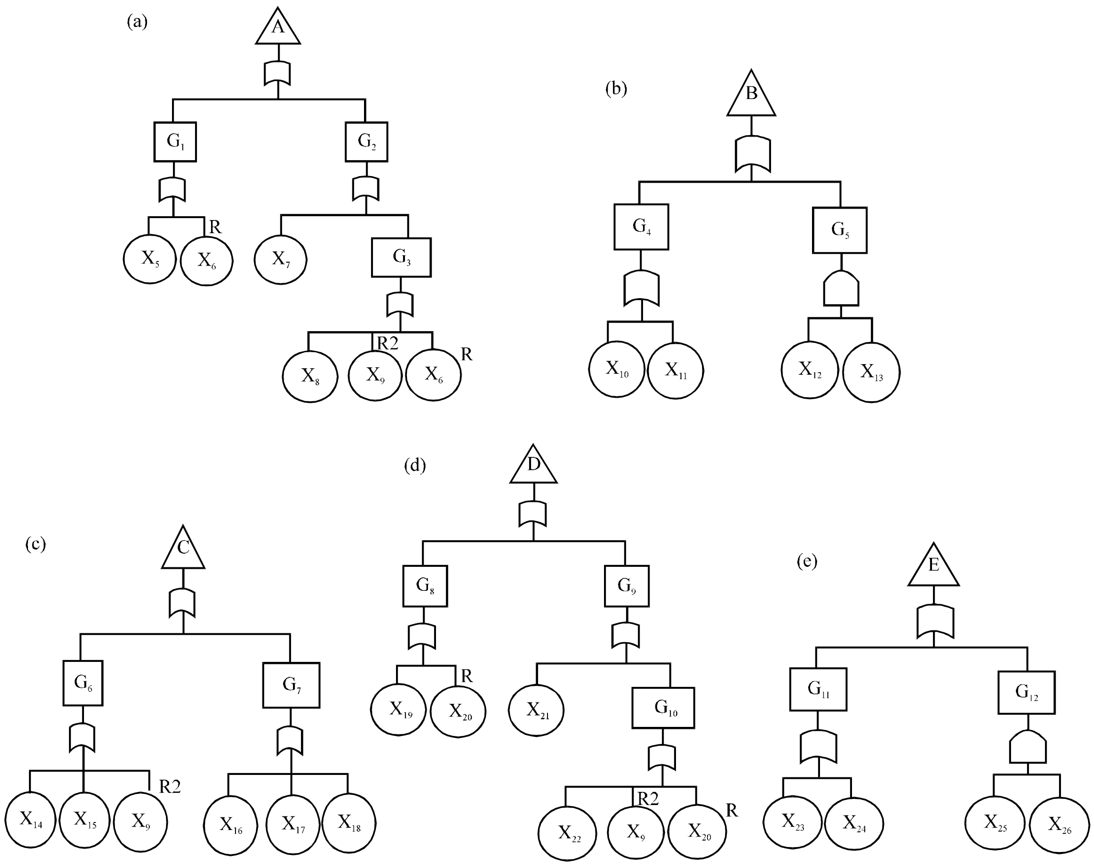



Fig. 2: Fault tree diagram of the jacket water cooling system. This figure describes about the overall fault tree diagram of jacket water cooling system. It includes both basic events and transfer gates. Detail of transfer gates are described in Fig. 3. And the descriptions of transfer gates are described in Table 2

are well maintained like on board systems, equipments are rarely to reach their failure states. But failures are still occurred in both main engine and auxiliary systems of ships. In the reliability analysis of jacket water cooling system, failure probability of basic events are obtained from the manufacturer and the reliability data handbook of Offshore Reliability Engineering Data handbook (OREDA) which can give the failure data with the most similar operational environment with onboard operation (SINTEF Industrial Management, 2002) and also from other reliability data handbook such as Non-Electrical Parts Reliability Data (Denson *et al*., 1991). Based on these data expert judgments are added to get the left and right fuzzy numbers of basic events. In this case, expert judgments are done by chief engineer, second engineer, third engineer and electrical engineer who had been worked on board. In addition to their expert knowledge, strong records of ship maintenance system (PMS, Prevented Maintenance System) are fed to experts to obtain the expert decision of the system.

Different kind of methods such as mean, median, maximum and mixed operators, etc., are in use to evaluate the fuzzy opinions of experts. In this study, the weighted a verage is used because of judgments




R = One time repeated event
R2 = Two times repeated event

Fig. 3(a-e): Transfer gates of the jacket water cooling system (a) Transfer gate (A), (b) Transfer gate (B), (c) Transfer gate (C), (d) Transfer gate (D) and (e) Transfer gate (E). This figure describes about detail of each transfer gate. Each transfer gate is composed with logic gates and basic events which includes in that system. Name of each basic events and their fuzzy probability of failure of each basic event is described in Table 1. Boolan algebra and fuzzy probability of failures are used to calculate the result of each transfer gate

come from different level of engineers. Let the triplet $G_{ij} = (a_{ij}, m_{ij}, b_{ij})$ represent the triangular fuzzy numbers, where i = 1, 2, 3,..., n and j = 1, 2, 3, 4 are the fuzzy probability given to even i by expert j. The expression for aggregating the judgments of experts in a fuzzy number is:

$$G_i = \frac{\sum_{j=1}^{4}(W_j \times G_{ij})}{\sum_{j=1}^{4} W_j} \quad (19)$$

where, $G_i$ represents the weighted average fuzzy probability of the event i and $W_j$ denotes the weight of the judgment of engineers. Fuzzy probabilities of the basic events are given in Table 1.

**Fuzzy fault tree calculation of the top event:** Detail descriptions of the transfer gates and middle gates of the fault tree diagram are explained in Table 2 and 3. By using fault tree analysis method fuzzy probability of the top gate can be found as follow:

$$A = \tilde{G}_1 + \tilde{G}_2 + \tilde{G}_3 = (\tilde{x}_5 + \tilde{x}_6) + \tilde{x}_7 + \tilde{G}_3 = (\tilde{x}_5 + \tilde{x}_6) + (\tilde{x}_7) + (\tilde{x}_8 + \tilde{x}_9)$$

$$B = \tilde{G}_4 + \tilde{G}_5 = (\tilde{x}_{10} + \tilde{x}_{11}) + (\tilde{x}_{12} \times \tilde{x}_{13})$$

$$C = \tilde{G}_6 + \tilde{G}_7 = (\tilde{x}_9 + \tilde{x}_{14} + \tilde{x}_{15}) + (\tilde{x}_{16} + \tilde{x}_{17} + \tilde{x}_{18})$$

$$D = \tilde{G}_8 + \tilde{G}_9 + \tilde{G}_{10} = (\tilde{x}_{19} + \tilde{x}_{20}) + \tilde{x}_{21} + \tilde{G}_{10} = (\tilde{x}_{19} + \tilde{x}_{20}) + \tilde{x}_{21} + (\tilde{x}_9 + \tilde{x}_{22})$$

$$E = \tilde{G}_{11} + \tilde{G}_{12} = (\tilde{x}_{23} + \tilde{x}_{24}) + (\tilde{x}_{25} \times \tilde{x}_{26})$$

$$\tilde{T} = \tilde{S}_1 + \tilde{S}_2 = (\tilde{x}_1 + \tilde{A} + \tilde{B} + \tilde{C} + \tilde{x}_2) + (\tilde{x}_3 + \tilde{D} + \tilde{E} + \tilde{x}_4)$$

Table 1: Fuzzy probability of failure of the basic events of jacket water cooling system

| Notation of basic event | Name of events | Probability ($m_i$) | $m_i$-$a_i$ and $b_i$- $m_i$ |
|---|---|---|---|
| $X_1$ | Cooling water piping system fails | 0.00001 | 0.0000025 |
| $X_2$ | H.T.F.W cooler fails | 0.000048 | 0.0000250 |
| $X_3$ | Lubrication oil cooler fails | 0.000135 | 0.0000300 |
| $X_4$ | Central cooler fails | 0.000080 | 0.0000100 |
| $X_5$ | H.T F.W temperature sensor fails | 0.000042 | 0.0000050 |
| $X_6$ | H.T F.W 3 ways valve control module fails | 0.000001 | 0.00000025 |
| $X_7$ | H.T F.W 3 ways valve mechanism fails | 0.000027 | 0.0000050 |
| $X_8$ | Solenoid valves fails | 0.000025 | 0.0000050 |
| $X_9$ | Fails of control supply air | 0.0006 | 0.0001500 |
| $X_{10}$ | H.T F.W pressure sensor fails | 0.000073 | 0.0000150 |
| $X_{11}$ | H.T F.W pump automatic control fails | 0.000075 | 0.0000150 |
| $X_{12}$ | H.T F.W pump No.1 fails | 0.00006 | 0.0000100 |
| $X_{13}$ | H.T F.W pump No.2 fails start on demand | 0.000051 | 0.0000050 |
| $X_{14}$ | Pressure control system fails | 0.000002 | 0.00000025 |
| $X_{15}$ | Solenoid valves fails | 0.000025 | 0.0000050 |
| $X_{16}$ | Water level sensor fails | 0.000077 | 0.0000050 |
| $X_{17}$ | Water Pump control fails | 0.000075 | 0.0000150 |
| $X_{18}$ | Failure of water pump | 0.000053 | 0.0000050 |
| $X_{19}$ | L.T F.W temperature sensor fails | 0.000042 | 0.0000050 |
| $X_{20}$ | L.T F.W 3 ways valve control module fails | 0.000001 | 0.00000025 |
| $X_{21}$ | L.T F.W 3 ways valve mechanism fails | 0.000027 | 0.0000050 |
| $X_{22}$ | Solenoid valves fails | 0.000025 | 0.0000050 |
| $X_{23}$ | L.T F.W pressure sensor fails | 0.000073 | 0.0000150 |
| $X_{24}$ | L.T F.W pump automatic control fails | 0.000075 | 0.0000150 |
| $X_{25}$ | L.T F.W pump No.1 fails | 0.00006 | 0.0000100 |
| $X_{26}$ | L.T F.W pump No.2 fails start on demand | 0.000051 | 0.0000050 |

This table describes about the triangular fuzzy No. of probability of failure of each basic events (failure $h^{-1}$). These data are got from the combination of failure rate data from hand book (OREDA offshore engineering reliability data handbook, 2002 and non electrical product reliability data handbook, 1991) and experts' judgments from engineers worked on board. Weighted average method as shown in Eq. 19 of main text is used to calculate the average of fuzzy probability of failure

Table 2: List of the transfer gates with respect to their function of failure calculation

| Name of transfer gate | Description of failure calculation |
|---|---|
| A | Failure of H.T.F.W temperature control system |
| B | Failure of primary circulation pumps and control system |
| C | Failure of high pressure F.W supply system |
| D | Failure of L.T.F.W temperature control system |
| E | Failure of secondary circulation pumps and control system |

This table describes the list of transfer gates which are used to calculate the sub-system of the fault tree system as shown in Fig. 2

By applying the Eq. 11 for calculating the fuzzy probability of transfer gate A:

$$\begin{aligned}\widetilde{A} &= (1-(1-0.000037)\times(1-0.00000075)\times(1-0.000022)\\ &\times(1-0.00002)\times(1-0.0045), 1-(1-0.000042)\times(1-0.000001)\\ &\times(1-0.000027)\times(1-0.00025)\times(1-0.0006), 1-(1-0.000047)\\ &\times(1-0.00000125)\times(1-0.000032)\times(1-0.00003)\times(1-0.00075))\\ &= (0.000529712, 0.00069494, 0.0008601633)\end{aligned}$$

Table 3: List of the gates with respect to their function of failure calculation

| Gate name | Description of failure calculation |
|---|---|
| $G_1$ | Failure of H.T F.W temperature control system |
| $G_2$ | H.T F.W 3 ways valves failure |
| $G_3$ | H.T F.W 3 ways valve pneumatic control fails |
| $G_4$ | H.T F.W circulation pump automatic control fails |
| $G_5$ | H.T F.W circulation pumps fails |
| $G_6$ | Hi pressure pressuring control system fails |
| $G_7$ | Failure of hi pressure water filling system |
| $G_8$ | Failure of L.T F.W temperature control system |
| $G_9$ | L.T F.W 3 ways valves failure |
| $G_{10}$ | L.T F.W 3 ways valve pneumatic control fails |
| $G_{11}$ | L.T F.W circulation pump automatic control fails |
| $G_{12}$ | L.T F.W circulation pumps fails |

This table describes the list of the logic gates of the fault tree system. Lower level of logic gates are composed of basic events and upper level logic gates are composed of both basic events and logic gates as shown in Fig. 3

Applying Boolean algebra the fuzzy probability of the top event can be expressed as follow:

$$\begin{aligned}\widetilde{T} &= \tilde{S}_1 + \tilde{S}_2 = (\tilde{x}_1 + \tilde{A} + \tilde{B} + \tilde{C} + \tilde{x}_2) + (\tilde{x}_3 + \tilde{D} + \tilde{E} + \tilde{x}_4)\\ &= (\tilde{x}_1 + \tilde{x}_2) + [(\tilde{x}_5 + \tilde{x}_6) + (\tilde{x}_7) + (\tilde{x}_8 + \tilde{x}_9)] + [(\tilde{x}_{10} + \tilde{x}_{11})\\ &+ (\tilde{x}_{12} \times \tilde{x}_{13})] + [(\tilde{x}_{14} + \tilde{x}_{15}) + (\tilde{x}_{16} + \tilde{x}_{17} + \tilde{x}_{18})] + (\tilde{x}_3 + \tilde{x}_4)\\ &+ [(\tilde{x}_{19} + \tilde{x}_{20}) + \tilde{x}_{21} + \tilde{x}_{22}] + [(\tilde{x}_{23} + \tilde{x}_{24}) + (\tilde{x}_{25} \times \tilde{x}_{26})]\end{aligned} \quad (20)$$

## RESULTS AND DISCUSSION

**Fuzzy failure probability of the top event:** Fuzzy probability of all transfer gates can be found by using fuzzy gates equations and the fuzzy probability of the top undesired event can be calculated by using the results of these transfer gates. Eq. 20 is used to calculate the top event (failure to maintain the desired temperature of the jacket water cooling system) and the result can be shown as a triangular fuzzy number (0.001252095, 0.001589956, 0.001927729) and the fuzzy probability of the final event in failure probability per hour can be shown as follow:

$$\mu_{\tilde{T}}(x) = \begin{cases} 0 & (x < 0.001252095) \\ \dfrac{x-a}{m-a} & (0.001252095 \le x \le 0.001589956) \\ \dfrac{b-x}{b-m} & (0.001589956 < x \le 0.001927729) \\ o & (x > 0.001927729) \end{cases}$$

**Fuzzy importance measure of basic events:** For calculating the fuzzy importance measure of the basic events, the probability of occurrence of top event in absence of basic event $x_i$, i = (1, 2, 3,..., 25, 26) is calculated as shown in Table 4. From these results, it can be known the level of importance of the component (basic event) to cause the undesired top event. In other words, this table can show the importance of the contribution a basic event in different cut sets of the system. But these results are in triangular fuzzy numbers, so they cannot be compared as

Table 4: Fuzzy failure probability of the top event in the absence of the basic events $x_i$

| Notation of basic event | Fuzzy failure probability of the top event in the absence of the basic events $x_i$ | | |
|---|---|---|---|
| | a | m | b |
| $X_1$ | 0.001244604 | 0.001579972 | 0.001915253 |
| $X_2$ | 0.001229123 | 0.001542030 | 0.001854864 |
| $X_3$ | 0.001147215 | 0.001455152 | 0.001763020 |
| $X_4$ | 0.001182177 | 0.001510077 | 0.001837894 |
| X5 | 0.001215140 | 0.001548021 | 0.001880817 |
| $X_6$ | 0.001251346 | 0.001588958 | 0.001926481 |
| $X_7$ | 0.001230122 | 0.001562998 | 0.001895789 |
| $X_8$ | 0.001232119 | 0.001564995 | 0.001897786 |
| $X_9$ | 0.000802456 | 0.000990550 | 0.001178613 |
| $X_{10}$ | 0.001194164 | 0.001517067 | 0.001839891 |
| $X_{11}$ | 0.001192166 | 0.001515070 | 0.001837894 |
| $X_{12}$ and $X_{13}$ | 0.001252092 | 0.001589953 | 0.001927725 |
| $X_{14}$ | 0.001250347 | 0.001587959 | 0.001925483 |
| $X_{15}$ | 0.001232119 | 0.001564995 | 0.001897786 |
| $X_{16}$ | 0.001180180 | 0.001513072 | 0.001845880 |
| $X_{17}$ | 0.001192166 | 0.001515070 | 0.001837894 |
| $X_{18}$ | 0.001204152 | 0.001537037 | 0.001869837 |
| $X_{19}$ | 0.001215140 | 0.001548021 | 0.001880817 |
| $X_{20}$ | 0.001251346 | 0.001588958 | 0.001926481 |
| $X_{21}$ | 0.001230122 | 0.001562998 | 0.001895789 |
| $X_{22}$ | 0.001232119 | 0.001564995 | 0.001897786 |
| $X_{23}$ | 0.001194164 | 0.001517067 | 0.001839891 |
| $X_{24}$ | 0.001192166 | 0.001515070 | 0.001837894 |
| $X_{25}$ and $X_{26}$ | 0.001252092 | 0.001589953 | 0.001927725 |

This table describes about the fuzzy probability of failure of top event (failure to maintain the desired temperature of the jacket water cooling system) without considering the failure effect of each basic event includes in the system. From these results, it can be know the level of importance of the component (basic event) to cause the undesired top event. In other words, this table can show the importance of the contribution a basic event in different cut sets of the system. But these results are in triangular fuzzy numbers, so they cannot be compared as real number. Fuzzy number ranking methods are used to determine the level of importance of each basic event and the result is shown in Table 5

Table 5: Comparison of fuzzy importance measure of the basic events of jacket water cooling system

| Notation of basic event | Ranking fuzzy No. method | Fuzzy distance method |
|---|---|---|
| $X_{12}$ and $X_{13}$ | 0.000530158 | 0.999400966 |
| $X_{25}$ and $X_{26}$ | 0.000530158 | 0.999400966 |
| $X_6$ | 0.000529826 | 0.999401960 |
| $X_{20}$ | 0.000529826 | 0.999401960 |
| $X_{14}$ | 0.000529493 | 0.999402957 |
| $X_1$ | 0.000526829 | 0.999410935 |
| $X_8$ | 0.000521834 | 0.999425894 |
| $X_{15}$ | 0.000521834 | 0.999425894 |
| $X_{22}$ | 0.000521834 | 0.999425894 |
| $X_7$ | 0.000521168 | 0.999427888 |
| $X_{21}$ | 0.000521168 | 0.999427888 |
| $X_5$ | 0.000516174 | 0.999442849 |
| $X_{19}$ | 0.000516174 | 0.999442849 |
| $X_2$ | 0.000514167 | 0.999448831 |
| $X_{18}$ | 0.000512511 | 0.999453820 |
| $X_{10}$ | 0.000505848 | 0.999473768 |
| $X_{23}$ | 0.000505848 | 0.999473768 |
| $X_{11}$ | 0.000505182 | 0.999475763 |
| $X_{17}$ | 0.000505182 | 0.999475763 |
| $X_{24}$ | 0.000505182 | 0.999475763 |
| $X_{16}$ | 0.000504521 | 0.999477760 |
| $X_4$ | 0.000503519 | 0.999480752 |
| $X_3$ | 0.000485196 | 0.999535620 |
| $X_9$ | 0.000330244 | 1 |

This table shows the level of importance of the component (basic event) to cause the undesired top event by comparing fuzzy failure probability by using two different methods. The second column shows the result of using ranking fuzzy number method. The lower the rank, the higher the importance of the component for the system is. The third column shows the result of using fuzzy distance method. The larger the distance, the higher the importance level of the component for the system is. From the results, it can be seen that both proposed methods give same ranks of fuzzy importance measure for basic events and the result can also be comparatively verified the results of the two proposed methods

real number. Fuzzy number ranking methods are used to determine the level of importance of each basic event.

Two fuzzy importance measures are calculated by applying fuzzy probability ranking method and Graded Mean Integration Representation (GMIR) distance method and the detail comparison of the results are shown in Table 5. From the results, it can be seen that both proposed methods give same ranks of fuzzy importance measure for basic events and the result can also be comparatively verified the results of the two proposed methods. As a qualitative analysis it can be clearly observed that the highest failure rate event of control air supply $X_9$ has the highest fuzzy importance measure as well as the most critically important event of the system. Due to the redundant configuration of H.T F.W pumps and L.T F.W pumps, they have the lowest fuzzy important measure even though their failure rates are higher than some of the equipments. The ranks of fuzzy importance measures of other basic events or equipments which are connected with OR gates from bottom layer to top undesired event are found out with their order of failure rates.

## CONCLUSION

In this study, fuzzy importance measure methods are presented to deal with two major aspects in reliability analysis of any onboard system. These are as follow:

- Describing the fuzzy importance measure evaluating procedure for a system in the case of operating different environments, process conditions, levels of maintenance and inspection and incomplete information of maintenance data
- To determine the critically importance of basic events by using fuzzy importance measure to improve the system reliability, availability and planning of future maintenance and inspection works

From the reliability analysis of jacket water cooling system has high reliability and it can be concluded that the repeated basic event $X_9$, failure of supply air, is the highest rank of fuzzy importance measure for the occurring the top event of the system. It further more shows the redundant installations of water circulation pumps are lowest in fuzzy important measure of the system. To improve the reliability of cooling water system, availability of supply air system should be well maintained and monitored, because it is not only high in fuzzy important measure but also the most repeated event of the system.

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