Failure Mode and Effect Criticality Analysis (FMECA) Fuzzy to Evaluate Critical Level on Main Engine Supporting System

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Abstract. Main engine is an important part as the prime mover on the ship. Main engine performs its functions supported by the main engine supporting system, such as: lubricating oil system, cooling system, fuel system, etc. These systems have many components that must be maintained. This is important to ensure each component works according to its function. While a failure occurs it has an impact, especially for safety. To determine the priority of maintenance on the equipment, the risk priority level method is used. In this research, the case study taken is the cooling system. Risk priority level is determined by the failure mode and effect criticality analysis (FMECA) approach based on the risk matrix of American Bureau Shipping (ABS). FMECA results are verified using the fuzzy theory simulation method. The result of ordinary FMECA ABS shows that as many as 47 failure modes in medium risk and 28 failure modes in the low risk level. However, from analysis of FMECA fuzzy there are 19 failure modes in the medium risk level and 56 failure modes in the low risk level. The use of fuzzy simulation is useful to reduce subjectivity in giving scores. Therefore, FMECA fuzzy shows a lower level of risk than ordinary FMECA ABS.

1. Introduction

Diesel engines are widely used as main propulsion on ships [1]. The cooling system is one of the important supporting systems to support engine performance. Cooling system functions as a cooler on the engine, such as: air cooler, lubricating oil cooler and fresh water cooler. The cooling system is divided into two system diagrams which consist of sea water system and fresh water system. To ensure the condition of the cooling system in a good performance condition, it is necessary to maintain a maintenance strategy for each main equipment that works on the system [2]. Maintenance strategies are useful for determining priorities and maintenance actions in maintaining the conditions of the assets [3].

There are many researchers who have conducted research in the field of maintenance strategies and failure pattern that occur in assets. The term six failure patterns on asset has been extensively studied since the 2000s, where the six types of failure are statistically 11% age related and 89% are random failure. Several methods have been developed in supporting maintenance decision making such as hazard studies, fault tree analysis (FTA), failure modes and effect analysis (FMEA), etc. [4].

The Failure Mode and Effect Analysis (FMEA) method provides a bottom-up approach to identifying the failure mode of equipment that causes the equipment to fail [5]. The application of
FMEA was applied to find out the cause of failure on components in some fields, such as: on the ship [6], oil and gas area [7], [8], manufacturing industry as a tool to determine reliability [9], [10]. The FMEA method in its development uses a combination of criticality to determine the critical level of equipment [11].

One of the criticality methods used at FMECA is the Risk Priority Number (RPN) [12]. However, the RPN method has weaknesses in determining risk priorities. This is related to the relationship in considering severity, occurrence and detection scores in risk implication. Therefore, in its development the RPN is modelled by the fuzzy logic [13], [14], ANOVA [5], ANP [15] and gray theory methods [16], [17].

This research develops FMECA model by adding criticality analysis for a case study on the cooling system. The risk analysis using fuzzy simulation approach based on ABS criteria to justify severity and likelihood assessments.

2. Methods
The improvement of FMECA model is used to determine maintenance priority equipment on the cooling system. The FMECA model used the ABS Classification criticality matrix to assess the risk level in each failure mode that occurred. FMECA results are verified using the fuzzy theory simulation method.

2.1. Development FMECA based on ABS Classification
Step 1. Function, Functional Failure, Failure Mode and Effect Setup
The first step in carrying out the FMECA model is to define the function of each equipment on the cooling system. Function that has been determined, then identified the possibility of functional failure. The next step is to identify the failure mode or cause of failure that causes functional failure. While the effects of failure are identified based on the impact caused by each failure mode. To make it easier to define failure mode, OREDA (Offshore Reliability Data Handbook) is used as a reference [18].

Step 2. Determination of Criticality Model
The criticality model is used as a measure of the risk level in each failure mode and effect based on ABS Classification guidelines [19]. Where this critical model considers the likelihood and severity factors which consist of loss of containment, safety and operational. The criteria for likelihood and severity levels are shown in tables 1-2. While the risk level is represented in a 4x5 matrix as shown in figure 1.

| Likelihood | 1 | 2 | 3 | 4 | 5 |
|------------|---|---|---|---|---|
| 4           | 5 | 6 | 7 | 8 | 9 |
| 3           | 4 | 5 | 6 | 7 | 8 |
| 2           | 3 | 4 | 5 | 6 | 7 |
| 1           | 2 | 3 | 4 | 5 | 6 |

**Figure 1. Risk matrix of ABS classification [19]**

| Severity Level | Descriptions for Severity Level |
|----------------|---------------------------------|
| 1              | Minor, Negligible,              |
| 2              | Major, Marginal, Moderate       |
| 3              | Critical, Hazardous, Significant|
| 4              | Catastrophic, Critical          |
Table 2. Likelihood level [19]

| Likelihood level | Likelihood Descriptor | Description          |
|------------------|-----------------------|----------------------|
| 1                | Improbable            | Fewer than 0.001 events/year |
| 2                | Remote                | 0.001 to 0.01 events/year |
| 3                | Occasional            | 0.01 to 0.1 events/year |
| 4                | Probable              | 0.1 to 1 events/year |
| 5                | Frequent              | 1 or more events/year |

2.2. Evaluation of FMECA using Fuzzy Logic Simulation
Transforming the vagueness of human feeling and recognition into a mathematical formula can use fuzzy logic simulation. The fuzzy logic provides measurement for uncertainties vague concepts. From many literatures, the FMECA Fuzzy concerned with the fuzzy rule base approach by using “If-Then” rules [20-22]. The steps of FMECA fuzzy are following [23]:

a) Fuzzification process uses linguistic variables to convert the three risk factors S, O and D into the fuzzy representations. Using the linguistic variables and their definitions, ranking three risk factors can be made in a scale basis. These inputs are then fuzzified to determine the degree of membership in each input class.

b) Rule evaluation consists of the expert knowledge about the interactions between various failure modes and effect that is represented in the form of fuzzy if–then rules. The outputs of the fuzzy inference system are variously named as ‘riskiness’, ‘critically failure mode’, ‘priority for attention’, and ‘fuzzy RPN’ in the fuzzy FMEA studies.

c) Defuzzification process creates a crisp ranking from the fuzzy RPN to give the prioritization level for the failure modes.

Figure 2. Fuzzy rule base technique [23]

Step 1. Membership Function Setup and Determine the Score of Fuzzy Numbers
The membership function is a function that represents the elements of a set of membership values at intervals [0,1]. The membership function can be represented in various ways, but the most common and widely used in systems made based on fuzzy logic is analytic representation. The membership function used in this research is the representation of triangles and trapezoidal curve. Figure 3 shows the representation of triangle and trapezoidal curve.

The input membership function consists of Severity (S), Occurrence (O) and Detection (D). Tables 4-5 membership functions and fuzzy numbers. Level of severity and occurrence are created from ABS
criteria, whereas the level of detection is modified from Wang [24], see Table 3. Severity (S), Occurrence (O) and Detection (D) have representation of triangle curve.

![Figure 3](image1.png)

**Figure 3.** On these figures show the representation of membership function, (a) representation of triangle curve, (b) representation of trapezoidal curve. Trapezoidal curve representation is basically like a triangle curve, but there are some points that have a value of degree membership 1.

| Likelihood level | Likelihood Descriptor | Description |
|------------------|-----------------------|-------------|
| 1                | Very High             | Very high chance the design control will detect a potential cause of failure or subsequent failure mode |
| 2                | High                  | High chance the design control will detect a potential cause of failure or subsequent failure mode |
| 3                | Medium                | Moderate chance the design control will detect a potential cause of failure or subsequent failure mode |
| 4                | Low                   | Low chance the design control will detect a potential cause of failure or subsequent failure mode |
| 5                | Very Low              | Very low chance the design control will detect a potential cause of failure or subsequent failure mode |
Table 4. Membership function of severity level

| Severity Level | Descriptions for Severity Level | Fuzzy Number |
|----------------|---------------------------------|--------------|
| 1              | Minor, Negligible (N1)          | [0 0.5 1]    |
| 2              | Major, Marginal, Moderate (M1)  | [1 1.5 2]    |
|                | Critical, Hazardous, Significant (S1) | [2 2.5 3]   |
| 4              | Catastrophic, Critical (C1)     | [3 3.5 4]    |

Table 5. Membership function of occurrence/likelihood level

| Likelihood level | Descriptions for Likelihood Level | Fuzzy Number |
|------------------|----------------------------------|--------------|
| 1                | Improbable (I2)                  | [0 0.5 1]    |
| 2                | Remote (R2)                      | [1 1.5 2]    |
| 3                | Occasional (O2)                  | [2 2.5 3]    |
| 4                | Probable (P2)                    | [3 3.5 4]    |
| 5                | Frequent (F2)                    | [4 4.5 5]    |

Table 6. Membership function of detection level

| Detection level | Descriptions for Detection Level | Fuzzy Number |
|-----------------|----------------------------------|--------------|
| 5               | Very Low (VL3)                   | [4 4.5 5]    |
| 4               | Low (L3)                         | [3 3.5 4]    |
| 3               | Medium (M3)                      | [2 2.5 3]    |
| 2               | High (H3)                        | [1 1.5 2]    |
| 1               | Very High (VH3)                  | [0 0.5 1]    |

Besides defining the input membership function, it is necessary to define the output membership function as an output of fuzzy values. Fuzzy value, hereinafter referred to as fuzzy risk priority number (FRPN) is used to evaluate the results of the criticality of FMECA which is done using ABS matrix. The level of FRPN is converted according to the ABS Matrix in Figure 1. Table 7 shows the conversion of FRPN level.

Step 2. Fuzzy Rules Setup

The number of input parameters is 4 for severity, 5 for occurrence and 5 for detection levels. So, the rules created are 100 rules. The rules are set up in if–then rules.

Step 3. FRPN output

In fuzzy analysis, rules will perform fuzzy processing algorithms using the Mamdani method.

Table 7. Membership function of FRPN output

| FRPN level | FRPN conversion | Type of Curve | Fuzzy Number |
|------------|-----------------|---------------|--------------|
| Very Low   | Low             | Trapezoidal   | [0 0 10 20]  |
| Low        | Medium          | Triangle      | [20 30 40]   |
| Medium     | High            | Triangle      | [40 50 60]   |
| High       | Very High       | Triangle      | [60 70 80]   |
| Very High  |                 | Trapezoidal   | [80 90 100 100] |
3. Result and Discussion
This research takes an object on a diesel engine that has specifications as in Table 8. FMECA analysis is carried out on the cooling system which is the supporting system of the diesel engine. From the results of the asset register, there are 10 main equipment.

| Table 8. Specification of diesel engine |
|-----------------|-----------------|
| Brand           | AKASAKA         |
| Model           | Mitsubishi 5UEC 45LA |
| Type            | 2 cycle/stroke  |
| Bore/stroke     | 450/1850        |
| Power           | 4118 kW / 150 rpm |

The initial step before defining function and functional failure is to create a functional block diagram. Figure 4-5 show the functional block diagrams that consist of cooling sea water system and cooling fresh water system.

![Figure 4. Cooling sea water system](image)

![Figure 5. Cooling fresh water system](image)

![Figure 6. Distribution of critical level of failure mode](image)
3.1. FMECA result based on ABS

The next step is to analyze by creating an FMECA worksheet, see Table 9-10. There are 10 main equipment analyzed and found 75 failure modes. The risk level assessment results on failure modes are 47 failure modes in the medium risk level and 28 failure modes in the low risk level. The risk level distribution of failure modes can be seen in figure 6. The summarize of critical level based on FMECA ABS is shown in Table 11.

Table 9. Example of FMECA worksheet (1/2)

| Equipment | Function                  | Functional failure (Loss of function) | Failure mode (Cause of failure) | Failure effect (What happens when it fails) |
|-----------|---------------------------|----------------------------------------|-------------------------------|---------------------------------------------|
| CO-TANK-001 FW EXP Tank | compressibility, shock caused by water hammer and absorbs excess water pressure caused by thermal expansion from main engine / aux. engine | A | 1 | The tank does not suit its function due to external leak/rupture | There is no absorb excess water pressure, can cause serious injuries for crew |
| | | | 2 | The tank does not suit its function due to plugged/choked inlet | The absorb excess water pressure caused by thermal expansion from main engine is not optimal |
| | | | 3 | The tank does not suit its function due to plugged/choked outlet | fresh water that is fed to jacket cool. FW pump is not optimal |

Table 10. Example of FMECA worksheet (2/2)

| Equipment | Failure mode (Cause of failure) | Failure effect (What happens when it fails) | Failure Rate (per year) | PoF | CoF | RISK |
|-----------|---------------------------------|---------------------------------------------|-------------------------|-----|-----|------|
| CO-TANK-001 FW EXP Tank | The tank does not suit its function due to external leak/rupture | There is no absorb excess water pressure, can cause serious injuries for crew | 0.0867 | 3 | 3 | Med |
| | The tank does not suit its function due to plugged/choked inlet | The absorb excess water pressure caused by thermal expansion from main engine is not optimal | 0.0867 | 3 | 2 | 1 | 2 | 2 | Med |
| | The tank does not suit its function due to plugged/choked outlet | fresh water that is fed to jacket cool. FW pump is not optimal | 0.0867 | 3 | 2 | 1 | 2 | 2 | Med |
The result of FMECA on cooling system there are six equipment that have highest score in medium criticality, FW. Expansion tank, FW. Generator, M/E FW Cooler, M/E LO Cooler, M/Eng Cool SW Pump, Air Cooler. The critical score of the equipment is 6, due to combination between likelihood score 3 and severity score 3. The levels of low risk are obtained by equipment that have failure modes with a critical score 4. The critical score is 4, due to combination between likelihood score 3 and severity score 1. The sea chest has low effect and severity in the event of a failure.

**Table 11. Critical level on equipment of cooling system**

| Equipment                          | Highest Risk Score | Critical Level   |
|------------------------------------|--------------------|------------------|
| FW EXP Tank                        | 6                  | Medium Risk      |
| FW Generator                       | 6                  | Medium Risk      |
| M/Eng FW Cooler                    | 6                  | Medium Risk      |
| No 2 M/Eng Jacket Cool FW Pump     | 5                  | Medium Risk      |
| No 1 M/Eng Jacket Cool FW Pump     | 5                  | Medium Risk      |
| M/Eng LO Cooler                    | 6                  | Medium Risk      |
| M/Eng Cool SW Pump                 | 6                  | Medium Risk      |
| Air Cooler                         | 6                  | Medium Risk      |
| SC (P)                             | 4                  | Low Risk         |
| SC (S)                             | 4                  | Low Risk         |

### 3.2. Simulation of FMECA based on Fuzzy Logic

The simulation of FMECA based on fuzzy logic is developed by MATLAB software. Steps of FMECA fuzzy simulation are following.

1. Creating membership function

The membership function is created based on value on Table 4-7. Figure 7 show the membership function of severity, likelihood, detection level and FRPN output. Membership functions of severity, likelihood, detection level have representations of triangles curve. While FRPN output has Trapezoidal and triangle curves. Membership function and fuzzy number are explained in subsection 2.2. step 1.
Figure 7. On these figures show the membership function plot in the fuzzy MATLAB, (a) membership function of severity level, (b) occurrence/likelihood, (c) detection level, (d) FRPN output, (e) input, process, output.
2. Creating fuzzy rules
The number of input parameters is 4 for severity, 5 for occurrence and 5 for detection levels. So, the rules created are 100 rules. The rules are set up in if–then rules, see figure 8.

3. Result of FMECA Fuzzy
The rules in figure 8 are simulated using Mamdani algorithm. Input and output in the Mamdani method is a fuzzy set. The Mamdani method used the function of the min and max aggregation implications, so the Mamdani method is called the min-max method (min-max inferencing).
For \( k = 1, 2, \ldots, n \), \( A_k^x \) expresses fuzzy set of pairs of antecedents of \( -x \) and \( B_k^y \) is a consequence fuzzy set of \( -y \). Figure 9 shows the example of fuzzy FRPN.

The risk level results based on fuzzy RPN, there are 56 failure modes in the medium risk level and 19 failure modes in the low risk level. Figure 10 shows the comparison of FMECA fuzzy and FMECA ABS.

![Comparison of FMECA Fuzzy Vs FMECA ABS](image)

**Figure 10.** The comparison FMECA Fuzzy and FMECA ABS

FMECA fuzzy shows a lower level of risk than ordinary FMECA ABS because the justification score on ordinary FMECA is directly given without fuzzy logic. So, the use of fuzzy simulation is useful to reduce subjectivity in giving scores. Table 12 shows the comparison result of critical level based on ordinary FMECA and FMECA Fuzzy.

| Equipment                     | Highest Risk Score of FMECA ABS | Highest Risk Score of FMECA Fuzzy | Critical Level FMECA ABS | Critical Level FMECA Fuzzy |
|-------------------------------|---------------------------------|-----------------------------------|--------------------------|----------------------------|
| FW EXP Tank                   | 6                               | 50                                | Medium Risk              | Medium Risk                |
| FW Generator                  | 6                               | 50                                | Medium Risk              | Medium Risk                |
| M/Eng FW Cooler              | 6                               | 50                                | Medium Risk              | Medium Risk                |
| No 2 M/Eng Jacket Cool FW Pump| 5                               | 30                                | Medium Risk              | Low Risk                   |
| No 1 M/Eng Jacket Cool FW Pump| 5                               | 30                                | Medium Risk              | Low Risk                   |
| M/Eng LO Cooler              | 6                               | 50                                | Medium Risk              | Medium Risk                |
| M/Eng Cool SW Pump            | 6                               | 50                                | Medium Risk              | Medium Risk                |
| Air Cooler                    | 6                               | 50                                | Medium Risk              | Medium Risk                |
| SC (P)                       | 4                               | 30                                | Low Risk                 | Low Risk                   |
| SC (S)                       | 4                               | 30                                | Low Risk                 | Low Risk                   |
4. Conclusion
The result of ordinary FMECA ABS shows that as many as 47 failure modes in medium risk and 28 failure modes in the low risk level. However, from analysis of FMECA fuzzy there are 19 failure modes in the medium risk level and 56 failure modes in the low risk level. FMECA fuzzy shows a lower level of risk than ordinary FMECA because the justification score on ordinary FMECA ABS is directly given without fuzzy logic. Therefore, the use of fuzzy simulation is useful to reduce subjectivity in giving scores.

Based on the results of the criticality and evaluation of FMECA, it can be determined the priority of maintenance of the equipment based on FMECA fuzzy analysis. The equipment with medium level of risk need to be prioritized maintenance strategies including preventive maintenance according to a specified schedule or time-based maintenance. However, for low risk level equipment can be applied planned corrective maintenance.

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