FMEA ANALYSIS ON OFFSHORE WIND TURBINES USING FUZZY MULTIMOORAMETHOD

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Abstract. Failure mode effective analysis (FMEA) is a quality instrument that is being used to recognize potential failure modes and its related consequences on different complex substructures in a system. The tool is effectively used for continuous improvement of efficiency, reliability, and quality. However, the traditional FMEA methods using risk priority number (RPN) values have been criticized for having many immanent limitations, affecting its effectiveness in real-world applications. Many risk priority models are emerging in the field of safety and reliability engineering. Among these models, Multi-criteria decision making (MCDM) methods are amongst the most widespread approaches employed to rank failure modes. The main aim of the present work is to implement FMEA analysis using fuzzy MULTIMOORA method. The proposed model has the competence of representing the imprecise knowledge and uncertainties of FMEA team members. FMEA analysis has been performed on offshore wind turbines consisting of four sub-assemblies for nine potential failure modes. The failure modes and its risk factors have been well-defined and appropriate linguistic variables are assigned to the failure modes according to the knowledge of team members. The responses of the team members have been aggregated and operated by the fuzzy model which prioritizes failure modes. The comparison of traditional FMEA rankings with the proposed model displays that a more precise and rational ranking can be attained by the incorporation of MULTIMOORA method using fuzzy set theory to FMEA. Keywords: FMEA, Fuzzy, MULTIMOORA, Reliability, RPN, Safety

1. INTRODUCTION

Safety is a major concern for program managers, design engineers, and reliability practitioners as the system designs have become more complex with increasing customer requirements. Failure modes and effects analysis (FMEA) initially came into existence in the aerospace industry during the Apollo mission where the influence of complex system failures on system performance, safety and mission success was to be evaluated during the early 1960s[1]. FMEA is usually a very attractive tool popularly used to assist the dependability and safety of products in various industries. Safety should be considered at the initial design stage to identify risks as early as possible which tends to reduce the lifecycle costs [2]. FMEA is applied at a component level and it assesses what can go wrong, and how it can affect the system. The main idea behind application of FMEA is to allow the specialists to set up the failure modes of a design, method, product or system in order to allocate the inadequate assets to the maximum risk items [3]. An effective FMEA provides potential failure preventive measures to assure high reliability, improve quality and reduction of failures [4].
FMEA is a methodology that uses potential failure modes which are aimed at preventing failures of a product by the evaluation of impacts, hence determining a priority of possible actions for reducing the occurrence of such failures. The application of FMEA is done at the system level, functional level or at the service level of a product [5]. The analysis of FMEA distinguishes the possible failure modes, evaluates the cause and effects of dissimilar failure modes and thereby diminishes the chance of high-risk failures. Conventional FMEA makes use of a risk priority number to calculate failure modes that's demarcated as the arithmetic product of risk elements O, S and D, where in O is the possibility of the failure, S is the significance of the failure, and D is the capacity to discover the failure before the effect is finished. For the calculation of the fee of RPN of every failure mode, each of risk elements are gauged on a mathematical scale from 1 to 10. The risk of a product or a system is directly proportional to the RPN of the failure mode. The RPNs are ranked and preventive measures and actions are engaged on the high-jeopardy failure modes [6]. Figure 1 shows the steps involved in the traditional FMEA method.

The conventional FMEA has gone under a scanner for a few decades and is of many intrinsic deficiencies leading to its limit in actual applications. It has been criticized due to various reasons which include its inefficacy to govern the priorities of potential risk failures. Diverse assimilation of risk factors may yield the equal value of RPN however their concealed risk outcomes may be numerous. This might cause a misuse of sources and a few high-hazard failure modes may match unobserved. The team members may not have a right skill set and pleasant degree of knowledge regarding the risk analysis of all failure modes. This arises due to the complexity of design, system or provider which makes the effects of risk evaluation display the characteristics of imprecision, fuzziness and uncertainty. The traditional analysis assumes that the risk factors contain equal weights which might not be applicable in real-life applications. The direct and indirect correlations among failure modes are not taken into consideration. The mathematical formula for calculating RPNs lacks scientific basis and considering the complexity of the systems involved nowadays, it needs to be efficient enough to encompass all the effects of risk factors. The traditional FMEA makes use of only three risk factors and ignores other potential risk factors such as economic aspects. The algebraic formula for evaluating RPN is highly sensitive to deviation in risk factor assessments. Slight deviations in one rating may have significant changes in RPN values, which is undesirable. The

![Figure 1. Traditional FMEA Methodology](image-url)
quantification of three risk factors are generally difficult for FMEA members as the inputs typically have vague information especially in a linguistic way like ‘important’, ‘high’, ‘low’. Hence rating them on a scale from 1 to 10 becomes a challenge to the team members and may cause uncertain judgments on the identified failure modes [7].

Numerous theories have been evolving to overcome vagueness and uncertainty arising in assessment of criticality. These include the fuzzy set, intuitionistic fuzzy set (IFS) and the Dempster–Shafer theory. The multi criteria choice making (MCDM) methods are emerging as the dominant procedures hired to prioritize the failure modes recognized through FMEA. These strategies enhance the effectiveness and experimental validity of consequences acquired from risk evaluation. The MCDM models below uncertain environment has a sequence of precise benefits which differentiate them from other FMEA models related to artificial intelligence. The FMEA approaches are experiencing detailed study as well as a continuous extension in the working envelope of its applications. Decision making tools such as uncertainty theories are used to model the obscurities arising from risk assessments. The MCDM practices have wide opportunities for improvement of the vitality analysis process of FMEA [8]. Figure 2 shows the numerous FMEA methods which are evolving in the field of safety and reliability engineering.

The fuzzy set theory is a fundamental concept of science. It handles imprecise information by using a certain formulation that manipulates the mathematical terms. The flexible or inaccurately defined boundaries of classes or categories can be represented and managed by the fuzzy set theory. This theory represents the classes by the use of characteristic functions which obtains its values from an ordered set of membership values. The membership function that defines the fuzzy set Z charts the elements of the universe X to the interval [0, 1], $Z: X \rightarrow [0,1]$. The membership function $f_Z(x)$ categorizes the fuzzy set Z in X and associates each point X with a real number in the unit interval. The association level of x with the set Z is represented by $f_Z(x)$. It is critical to analyze the type of fuzzy set for the criteria of its aptness for handling the succeeding optimization methods. The commonly used groups of the membership functions which are well defined in the real numbers space trapezoidal, triangular and exponential membership functions [9]. The fuzzy set takes care of the uncertainties resulting from human judgements on risk factors. The fuzzy set theory laid foundation for a risk priority model for prioritizing the failure modes and this led to a proposal of
MULTIMOORA method. The fuzzy ratings assessed the risk factors and the relative weights and the ranking of failure modes was accomplished through a comprehensive MULTIMOORA method [10].

The MCDM methods can be used amongst a number of team members or analysts who are experts in their respective areas. In the present study, floating off-shore wind turbines are considered for FMEA evaluation. The necessary data required for evaluation is obtained by the risk assessment on the off-shore wind turbines using correlation FMEA [11]. The present research mainly focuses on the systematic investigation of fuzzy MULTIMOORA method for evaluating on off shore wind turbines.

2. FLOATING OFFSHORE WIND TURBINES

Floating offshore wind turbine (FOWT) is a recent approach towards the demand for renewable sources of energy. Floating offshore wind turbines could be a game-changer as it has a lot of opportunities to offer. They can be installed in deep water sites with dynamic and harsh wind conditions. They provide a lot of environmental benefits compared to traditional wind turbine installation. The major drawbacks are the cost of installation of FOWT along with maintenance and experience of the workers. The location can be a disadvantage due to high lead repair time. An effective risk assessment would significantly reduce the corrective maintenance costs. FMEA is a widely applied methodology on the risk assessment of FOWT. The incorporation of FMEA to FOWT has drawbacks as it has a lot of complex parts and the FMEA is incapable of including these risk parameters [12]. In this study, we compare the nine potential failure modes of FOWT by using the RPN ratings of the failure modes already conducted on the four subassemblies of the offshore wind turbines [11]. The uncertainty theories can be used for risk assessment hence we use the fuzzy MULTIMOORA method for the FMEA analysis.

The FOWT is a multi-functional system. Table 1 describes the various subassemblies and their respective potential failure modes. The application of FMEA calls for the categorization of failure modes rendering to diverse system capabilities which are greater accurate for gauging the risk and reliability. The sub-assemblies are categorized according to the main functions of a driven FOWT. Table 2 relates the failure modes and corresponding reasons with end effects it could have on the system. The severity, occurrence and detection ratings for the failure modes are defined by Table 3, Table 4 and Table 5 respectively. Table 6 shows the RPN rating as the arithmetic multiplication of risk factors.

| Subassemblies                        | Failure Modes |
|--------------------------------------|---------------|
| Blade system                         | The blades culpabilities are connected to structural failures which include fatigue of the fibrous composite materials used. |
| Generator components                 | The leading faults in electrical components are due to short-circuits or open-circuit of the winding or due to overheating. |
| Transmission system (Bearing, Gearbox and Coupling) | The gearbox is susceptible to shock loads triggered by the variability of the wind speeds and the corrosion. |
| Support system (Nacelle tower, mooring system, floating foundation) | The crucial failure reasons of the support structure are corrosion, hull collision and welding cracking. |
| Auxiliary system (lightning protection) | The primary failure modes are hydraulic pressure error and temperature. |
system, cooling system, hydraulic system)

Table 2. End Effects of failure modes in subassemblies

| Subassembly       | Failure Modes                          | End Effects               | Cause of Failures                      |
|-------------------|----------------------------------------|---------------------------|----------------------------------------|
| A. Generator      | 1. Deformation of bearing              | Equipment impairment      | Over tightening or loosening of bearing shaft |
|                   | 2. Overheat                            | FOWT system shutdown      | Disproportionate system oscillation     |
|                   | 3. Winding failure                     | FOWT system shutdown      | Winding corrosion                       |
| B. Electrical controls | 4. Conversion failure             | Disconnection from grid   | Invert power input error                |
|                   | 5. Transform winding failure           | Disconnection from grid   | Iron core corrosion                     |
|                   | 6. Output voltage error                | Disconnection from grid   | Friction between rotor and stator       |
|                   | 7. Yaw positioning inaccuracy          | Inefficiency              | Yaw damper inaccuracy                   |
| C. Support system | 8. Fracture of mooring line            | FOWT system closure       | Fatigue damage                          |
| D. Auxiliary systems | 9. Failure of cooling system      | FOWT system closure       | Pipeline leakage                        |

Table 3. Severity Ratings

| Scale | Description | Criteria                          |
|-------|-------------|-----------------------------------|
| 1     | Minor       | Electricity produced but repair necessary |
| 2     | Marginal    | Decrease in the capacity to produce electricity |
| 3     | Critical    | Loss of capacity to produce electricity |
| 4     | Catastrophic| Major impairment to the turbine   |

Table 4. Occurrence Ratings

| Scale | Description | Criteria                          |
|-------|-------------|-----------------------------------|
| 1 to 2| Extremely   | Probability is less than 0.0001   |
| 3 to 5| Remote      | Probability ranges from 0.0001 and 0.0001 |
| 6 to 8| Occasional  | Probability ranges from 0.0001 and 0.01 |
| 9 to 10| Frequent    | Probability is more than 0.01     |

Table 5. Detection Ratings

| Scale | Description   | Criteria                          |
|-------|---------------|-----------------------------------|
| 1 to 2| Practically   | Existing checking procedures always spot the failure |
| 3 to 5| High          | Good Probability that existing monitoring procedures will spot the failure |
Table 6. RPN Ratings

| Failure Mode                          | S | O | D | RPN |
|---------------------------------------|---|---|---|-----|
| 1. Bearing Deformation                | 4 | 6 | 6 | 144 |
| 2. Overheat                           | 3 | 7 | 6 | 126 |
| 3. Winding Failure                    | 4 | 8 | 7 | 224 |
| 4. Conversion Failure                 | 3 | 7 | 8 | 168 |
| 5. Transformation winding failure     | 3 | 8 | 8 | 192 |
| 6. Output Voltage error               | 3 | 7 | 8 | 168 |
| 7. Yaw positioning inaccuracy         | 3 | 7 | 6 | 126 |
| 8. Mooring line fracture              | 4 | 6 | 8 | 192 |
| 9. Cooling system failure             | 4 | 6 | 8 | 192 |

3. FUZZY MULTIMOORA METHOD

Multi-Objective optimization with the aid of ratio analysis (MOORA) is the idea which comes under MULTIMOORA method. MCDM technique makes use of a new threat precedence model where fuzzy set concept and MULTIMOORA technique are implemented for the evaluation of failure modes and rating in FMEA. The chance elements and their relative weights are pondered as fuzzy variables and calculated via the usage of fuzzy linguistic phrases and fuzzy rankings. The risk ranking of the failure modes is described using a complete MULTIMOORA method which aids in taking preventive movements for safety and reliability improvement [12]. Figure 3 indicates the whole method for imposing the MULTIMOORA model.

3.1 Methodology

The following steps are followed to prioritize failure modes using fuzzy MULTIMOORA method.

**Step 1 - Objectives of risk evaluation is recognized and FMEA scope is described.**

The fundamental step is outlining the objectives of risk assessment. It is significant to give condensed thought to this step as it will govern the whole process of risk assessment and ranking procedure. The scope of the FMEA analysis has been well well-defined to attain the desired rankings.
Step 2 - FMEA team is assembled and all potential failure modes enlisted.

A team of cross-functional specialists has to be fashioned considering the specific hassle scope and its complete size. All capability failure modes in conjunction with their reasons are enlisted the use of Brainstorming periods and cause-effect illustrations and their ability outcomes for every sub-function are analysed. To investigate the MULTIMOORA method, we have taken two team members having equal weight (0.5). We consider the same failure modes considered for the calculation of RPN according to Table 6. For our convenience, we name it FM1, … FM9. Instead of giving numbers as ratings, the two team members can rate the failure modes and risk factors in linguistic terms which are used in everyday language. The linguistic ratings given by the two team members (TM1, TM2) are represented in Table 7.

### Table 7. Team Members Ratings

| Failure Modes | TM1 |      | TM2 |      |
|---------------|-----|------|-----|------|
|               | O   | S    | D   | O   | S    | D   |
| FM 1          | M-H | V-H  | M-H | H   | E-H  | M-H |
| FM 2          | H   | M-H  | M-H | M-H | H    | M-H |
| FM 3          | V-H | V-H  | H   | E-H | H    | M-H |
| FM 4          | H   | M-H  | H   | M-H | M    | V-H |
| FM 5          | V-H | M-H  | H   | H   | H    | H   |
| FM 6          | H   | M-H  | H   | M-H | H    | H   |
| FM 7          | H   | M-H  | M-H | H   | M    | M-H |
| FM 8          | M-H | V-H  | H   | M-H | H    | H   |
| FM 9          | M-H | V-H  | H   | H   | E-H  | H   |

### Table 8. Ratings for Weights
Step 3 - Related risk factors are defined and suitable linguistic variables are selected.

A definite finite set of risk elements and their calculation metrics are established to evaluate the hazard of failure modes. We need to choose suitable linguistic terms for the significance weights of risk factors and the scores of failure modes concerning every threat issue. The linguistic terms for risk factors and weights are transformed into fuzzy numbers with the assistance of their fuzzy equivalents shown in Table 9 and Table 10 respectively. Hence the converted fuzzy values for our ratings are shown in Table 11 and Table 12. The two team members are indicated by TM1 and TM2.

### Table 9. Risk Factors Fuzzy Equivalents

| Risk factors | Linguistic ratings | Fuzzy equivalents |
|--------------|--------------------|-------------------|
| Extremely Low (E-L) | (0, 0, 0, 0) |
| Very Low (V-L) | (0, 0, 1, 2) |
| Low (L) | (1, 2, 2, 3) |
| Medium Low (M-L) | (2, 3, 4, 5) |
| Medium (M) | (4, 5, 5, 6) |
| Medium High (M-H) | (5, 6, 7, 8) |
| High (H) | (7, 8, 8, 9) |
| Very High (V-H) | (8, 9, 10, 10) |
| Extremely High (E-H) | (10, 10, 10, 10) |

### Table 10. Weights Fuzzy Equivalents

| Weights | Linguistic ratings | Fuzzy equivalents |
|---------|--------------------|-------------------|
| Extremely Low (E-L) | (0, 0, 0, 0) |
| Very Low (V-L) | (0, 0, 1, 2) |
| Low (L) | (1, 2, 2, 3) |
| Medium Low (M-L) | (2, 3, 4, 5) |
| Medium (M) | (4, 5, 5, 6) |
| Medium High (M-H) | (5, 6, 7, 8) |
| High (H) | (7, 8, 8, 9) |
| Very High (V-H) | (8, 9, 10, 10) |
| Extremely High (E-H) | (10, 10, 10, 10) |

### Table 11. Equivalent Fuzzy Ratings for Risk Factors

| Failure modes | O | S | D |
|---------------|---|---|---|
| **FM 1** | (5, 6, 7, 8) | (8, 9, 10, 10) | (5, 6, 7, 8) |
| **FM 2** | (7, 8, 8, 9) | (5, 6, 7, 8) | (5, 6, 7, 8) |
| **FM 3** | (8, 9, 10, 10) | (5, 6, 7, 8) | (7, 8, 8, 9) |
| **FM 4** | (7, 8, 8, 9) | (5, 6, 7, 8) | (5, 6, 7, 8) |
| **FM 5** | (8, 9, 10, 10) | (7, 8, 8, 9) | (7, 8, 8, 9) |
| **FM 6** | (7, 8, 8, 9) | (5, 6, 7, 8) | (7, 8, 8, 9) |
| **FM 7** | (7, 8, 8, 9) | (5, 6, 7, 8) | (5, 6, 7, 8) |
| **FM 8** | (5, 6, 7, 8) | (8, 9, 10, 10) | (5, 6, 7, 8) |
| **FM 9** | (5, 6, 7, 8) | (8, 9, 10, 10) | (7, 8, 8, 9) |

### Table 12. Equivalent Fuzzy Ratings for Weights

| Weights | O | S | D |
|---------|---|---|---|
| **TM1** | (5, 6, 7, 8) | (7, 8, 8, 9) | (10, 10, 10, 10) |
| **TM2** | (7, 8, 8, 9) | (10, 10, 10, 10) | (8, 9, 10, 10) |

Step 4 - Assembled the team members’ linguistic assessments.
The collective fuzzy rankings of failure modes regarding every risk factor can be calculated to develop the fuzzy group assessment matrix after the FMEA crew contributors give their selections on chance elements using linguistic phrases. The aggregation for risk factors given by Table 7 is calculated by equation (1) and for aggregation of weights as shown in Table 8 is calculated by equation (2).

\[ r_{ij} = (r_{i1j}, r_{i2j}, r_{i3j}, r_{i4j}) = \left( \sum_{k=1}^{l} \lambda_k r_{i1k}, \sum_{k=1}^{l} \lambda_k r_{i2k}, \sum_{k=1}^{l} \lambda_k r_{i3k}, \sum_{k=1}^{l} \lambda_k r_{i4k} \right) \]

(1)

The aggregated fuzzy equivalent of weight of each risk factor \( w_j \) is calculated as

\[ w = (w_{j1}, w_{j2}, w_{j3}, w_{j4}) = \left( \sum_{k=1}^{l} \lambda_k w_{j1k}, \sum_{k=1}^{l} \lambda_k w_{j2k}, \sum_{k=1}^{l} \lambda_k w_{j3k}, \sum_{k=1}^{l} \lambda_k w_{j4k} \right) \]

(2)

### Table 13. Aggregated Fuzzy Ratings

| FM  | O            | S            | D            |
|-----|--------------|--------------|--------------|
| 1   | (6,7,7,5,8.5)| (9,9.5,10,10)| (5,6,7,8)    |
| 2   | (6,7,7,5,8.5)| (6,7,7,5,8.5)| (5,6,7,8)    |
| 3   | (9,9.5,10,10)| (7,5,8,5,9,9,5)| (6,7,7,5,8,5)|
| 4   | (6,7,7,5,8,5)| (4,5,5,5,7,5,7)| (7,5,8,5,9,9,5)|
| 5   | (7,5,8,5,9,9,5)| (6,7,7,5,8,5)| (7,8,8,9)    |
| 6   | (6,7,7,5,8,5)| (6,7,7,5,8,5)| (7,8,8,9)    |
| 7   | (7,8,8,9)   | (4,5,5,5,6,7)| (5,6,7,8)    |
| 8   | (5,6,7,8)   | (7,5,8,5,9,9,5)| (7,8,8,9)    |
| 9   | (6,7,7,5,8,5)| (9,9.5,10,10)| (7,8,8,9)    |
| Weights | (0,6,0,7,0,75,0,85)| (0,85,0,95,0,9,0,95)| (0,9,0,95,1,1)|

\[ \hat{r} = r_1 = 26.4, \quad r_2 = 26.37, \quad r_3 = 24.443 \]

Step 5 - Normalized fuzzy assessment matrix is developed using the fuzzy ratio system which describes normalization of the fuzzy numbers.

The normalization is accomplished with the aid of comparing appropriate values of fuzzy numbers.

The aggregated fuzzy values are calculated by “(3)” and “(4)” is used to calculate \( \hat{r} \). The normalized fuzzy assessment matrix is shown in Table 14.

\[ x_{ij} = (x_{ij1}, x_{ij2}, x_{ij3}, x_{ij4}) = \left( w_{j1} \frac{r_{ij1}}{r}, w_{j2} \frac{r_{ij2}}{r}, w_{j3} \frac{r_{ij3}}{r}, w_{j4} \frac{r_{ij4}}{r} \right) \]

(3)

\[ r_j = \sqrt{\sum_{i=1}^{m} r_{ij}^2} \]

(4)

### Table 14. Normalized Fuzzy Assessment Matrix
Failure Modes | O | S | D
|-----------------|------------|------------|------------|
| FM 1            | (0.1364,0.1857,0.2131,0.2738) | (0.2901,0.3423,0.3413,0.3603) | (0.184,0.2332,0.286,0.373) |
| FM 2            | (0.1364,0.1857,0.2131,0.2738) | (0.1934,0.2522,0.256,0.3063) | (0.184,0.2332,0.286,0.373) |
| FM 3            | (0.2046,0.252,0.2842,0.3272) | (0.2418,0.3063,0.3072,0.3423) | (0.221,0.2721,0.307,0.378) |
| FM 4            | (0.1364,0.1857,0.2131,0.2738) | (0.1451,0.1982,0.256,0.2542) | (0.276,0.3304,0.368,0.348) |
| FM 5            | (0.1705,0.2255,0.2558,0.306) | (0.1934,0.2522,0.256,0.3063) | (0.258,0.3109,0.327,0.368) |
| FM 6            | (0.1364,0.1857,0.2131,0.2738) | (0.1934,0.2522,0.256,0.3063) | (0.258,0.3109,0.327,0.368) |
| FM 7            | (0.1592,0.1857,0.2742,0.3899) | (0.1451,0.1982,0.2048,0.2522) | (0.184,0.2332,0.286,0.373) |
| FM 8            | (0.1137,0.1592,0.1989,0.2577) | (0.2418,0.3063,0.3072,0.3423) | (0.258,0.3109,0.327,0.368) |
| FM 9            | (0.1364,0.1857,0.2131,0.2738) | (0.2901,0.3423,0.3413,0.3603) | (0.258,0.3109,0.327,0.368) |

Step 6 - The fuzzy reference point technique

The fuzzy maximal objective reference point (MORP) vector \( r^* = (x_1^*, x_2^*, \ldots, x_n^*) \) is attained according to the matrix \( X = [x_{ij}]_{m \times n} \). The \( j \)-th coordinate of the reference point be similar to the fuzzy maximum or minimum of the \( j \)-th risk factor \( x_j^* \) and can be calculated by \( (5) \)

\[
 x_j^* = \begin{cases} 
 (\max x_{j1}, \max x_{j2}, \max x_{j3}, \max x_{j4}), & j \leq g; \\
 (\min x_{j1}, \min x_{j2}, \min x_{j3}, \min x_{j4}), & j > g 
\end{cases} 
\]  

\( (5) \)

The distance of each failure mode from the fuzzy MORP can be calculated by using \( (6) \). The ranking orders of all failure modes are defined according to the eccentricity from the reference point.

\[
 d_i = \max d(x_j^*, x_{ij}) 
\]  

\( (6) \)

Step 7 - The final rankings are obtained from the fuzzy full multiplicative form as indicated in Table 15.

**Table 15. Fuzzy Multiplicative Form**

| Failure Modes | \( Y_i \) | \( Y_i' \) | Ranking |
|---------------|------------|------------|---------|
| FM 1          | (0.6106,0.7611,0.8409,0.9614) | 2.376 | 5 |
| FM 2          | (0.5139,0.6711,0.7555,0.9073) | 2.135 | 8 |
| FM 3          | (0.6673,0.8303,0.9892,1.0121) | 2.548 | 2 |
| FM 4          | (0.5576,0.7142,0.8373,0.9146) | 2.258 | 7 |
| FM 5          | (0.6217,0.7886,0.8391,0.9804) | 2.418 | 3 |
| FM 6          | (0.5876,0.7488,0.7964,0.9482) | 2.309 | 6 |
| FM 7          | (0.4883,0.617,0.7185,0.8694) | 2.023 | 9 |
| FM 8          | (0.6132,0.7763,0.8334,0.9682) | 2.388 | 4 |
| FM 9          | (0.6843,0.8389,0.8818,1.0023) | 2.549 | 1 |
Step 8 - Examine the outcomes and develop recommendations to reinforce the system performance.

The contrast of the fuzzy MULTIMOORA with the RPN method is shown in Table 16.

| Failure Modes | RPN | MULTIMOORA |
|---------------|-----|-------------|
| FM1           | 7   | 5           |
| FM2           | 9   | 8           |
| FM3           | 1   | 2           |
| FM4           | 6   | 7           |
| FM5           | 4   | 3           |
| FM6           | 5   | 6           |
| FM7           | 8   | 9           |
| FM8           | 2   | 4           |
| FM9           | 3   | 1           |

4. CONCLUSIONS

- The rankings obtained from the fuzzy MULTIMOORA method is compared from the rankings obtained from the traditional RPN method.
- The fuzzy MULTIMOORA methods encompasses all the uncertainties and vagueness of the data and is expected to provide effective FMEA rankings.
- We have successfully implemented the MULTIMOORA model for the FMEA analysis and obtained comparable priorities of failure modes.
- This model can also be extended to additional team members, failure modes and risk factors depending upon the requirement and complexity of the system to be analyzed.

REFERENCES

[1] Khairul Annuar Abdullah and Mohd Salihin Ngadiman 2005 Development of FMEA Information System for Manufacturing Industry, International Conference on Modeling and Analysis of Semiconductor Manufacturing Malaysia

[2] Tommaso Sgobba, Firooz Allahdadi A, Isabelle Rongier and Paul Wilde D 2013 Safety Design for Space Operations (Third Edition) USA Butterworth-Heinemann publications, 2013 pp 337-469

[3] Hu-Chen Liu 2016 FMEA Using Uncertainty Theories and MCDM Methods, Springer Science, Singapore pp 2-9

[4] Liu HC and You J X 2016 Failure mode and effect analysis under uncertainty: an integrated multiple criteria decision-making approach, IEEE Transactions Reliability pp 1027-1042

[5] Duane Kritzinger 2017 Failure Modes and Effects Analysis Author links open overlay panel Aircraft System Safety Assessments for Initial Airworthiness Vol 5 pp 101-132

[6] Stamatis DH 2003 Failure mode and effect analysis: FMEA from theory to execution New York 2003
[7] Haibin Liu, Xinyang Deng and Wen Jiang 2017 Risk Evaluation in Failure Mode and Effects Analysis Using Fuzzy Measure and Fuzzy Integral School of Electronics and Information

[8] Carlson C 2012 Effective FMEAs: achieving safe, reliable, and economical products and processes using failure mode and effects analysis New Jersey Wiley

[9] Abdelgawad M and Fayek A R 2010 Risk management in the construction industry using combined fuzzy FMEA and fuzzy AHP J. of construction Engg and Management Vol 136 Issue 9 pp 1028–1036

[10] Liu HC and Fan XJ Evaluating the risk of failure modes with extended MULTIMOORA method under fuzzy environment, Engg. Applications of Artificial Intelligence Vol 34 pp 168–177

[11] Jichuan Kangb and Liping Sunb 2017 Risk assessment of floating offshore wind turbine based on correlation-FMEA, Ocean Engineering Vol 129 pp 382–388

[12] Brauers WKM and Zavadskas EK, 2010 Project management by MULTIMOORA as an instrument for transition economies, Technological and Economic Development of Economy Vol 16 Issue 1 pp 5–24

[13] Brauers WKM and 2012 Zavadskas EK, Robustness of MULTIMOORA: a method for multi-objective optimization Informatica Vol 23 Issue 1 pp 1–25

[14] Brauers WKM and Zavadskas EK 2011 MULTIMOORA optimization used to decide on a bank loan to buy property, Technological and Economic Development of Economy Vol 17 Issue 1 pp 174