Proceedings of the Canadian Society for Mechanical Engineering International Congress
32nd Annual Conference of the Computational Fluid Dynamics Society of Canada
Canadian Society of Rheology Symposium
CSME-CFDSC-CSR 2025
May 25–28, 2025, Montréal, Québec, Canada

ENHANCED FAILURE MODE EFFECT ANALYSIS METHODOLOGY IN THE RISK ASSESSMENT OF MARINE MACHINERY SYSTEMS

E. Ibazebo[1], V. Savsani[1,2], A. Siddhpura[1], M. Siddhpura[1], P. Savsani[1,3]
[1]Mechanical Engineering Department, Engineering Institute of Technology, West Perth, Australia
[2]Mechanical Engineering Department, Canadore College, North Bay, Ontario, Canada
[3]Mechanical Engineering Department, Cambrian College, Sudbury, Ontario, Canada

Abstract—In the marine industry, machinery failure has been cited as the foremost cause of shipping incidents. No matter how well designed, marine machinery systems will not remain safe and reliable if not properly maintained. The challenge in the industry is how to maintain such complex systems. One of the major problems is the selection of an appropriate maintenance strategy for the various components of the system. In deciding on the appropriate maintenance strategy, a thorough risk analysis must be carried out to identify the most critical components of the various systems. Different techniques such as failure mode effect analysis (FMEA) have been used in the industry to prioritize risk of failure modes. The classical failure mode and effect analysis employed by the industry has been criticized as having some flaws, which include subjective risk prioritization and lack of comprehensive evaluation. This study presents an enhanced FMEA methodology for risk assessment in marine machinery systems. By integrating two Multi-Criteria Decision-Making (MCDM) tools—Fuzzy Analytic Hierarchy Process (FAHP) and Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (FTOPSIS)—the proposed methodology addresses the limitations of the traditional FMEA. The FAHP method refines the weight allocation process for risk factors using expert judgment while accounting for uncertainty, and FTOPSIS ranks failure modes based on their proximity to ideal solutions. The involvement of multiple subject matter experts (SMEs) ensures diverse perspectives, improving the robustness of the analysis. The practical findings of this paper demonstrates that traditional RPN can mis-prioritize failure modes. The FAHP-FTOPSIS approach provides more targeted, expert-driven insights, and reinforces the need for advanced methodologies in critical, high-stakes marine engineering applications where failure prevention is crucial.

Keywords-failure mode and effects analysis; multi-criteria decision-making; fuzzy analytic hierarchy process; fuzzy technique for order of preference by similarity to ideal solution

I. INTRODUCTION

The marine industry is a highly safety-critical sector where machinery failure remains a leading cause of shipping incidents. Machinery systems will not remain safe and reliable without proper maintenance, and ensuring the integrity of these systems requires the implementation of an effective maintenance strategy that considers the various risks associated with component failures. However, selecting the appropriate maintenance approach poses a significant challenge for maintenance practitioners, due to the complexity and interdependence of marine machinery components.

Risk assessment plays a crucial role in determining which components require the most attention. One of the widely employed tools to evaluate and prioritize marine machinery systems failure modes based on their severity, occurrence, and detectability is Failure Mode and Effect Analysis (FMEA). However, traditional FMEA has been criticized for its subjectivity, inconsistency in risk prioritization, and lack of a comprehensive evaluation framework [1]. Risk in the FMEA process is represented in the form of a Risk Priority Number (RPN). The higher the RPN value, the higher the risk of system failure. This RPN approach may lead to misjudgment of critical failure modes, resulting in suboptimal maintenance strategies.

To address these limitations, this paper presents an enhanced FMEA methodology by integrating fuzzy logic into two Multi-Criteria Decision-Making (MCDM) tools – Fuzzy Analytic Hierarchy Process (FAHP) and Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (FTOPSIS). The FAHP method refines risk factors weightings using expert judgements while incorporating uncertainty, thereby improving the accuracy of risk assessments. The FTOPSIS technique ranks failure modes based on their closeness to ideal solutions, thus ensuring a more rational prioritization. The incorporation of diverse perspectives by multiple subject matter experts (SMEs) enhances the robustness of the analysis. The proposed FAHP-FTOPSIS approach addresses the shortcomings of the traditional

FMEA by providing a more reliable and targeted risk assessment framework.

The practical findings of this paper offer a structured approach for identifying, evaluating, and prioritizing potential failure modes in marine machinery systems, enabling ship maintenance practitioners to proactively mitigate risks, thus enhancing the reliability and safety of marine operations, optimizing resource allocation, and reducing downtime.

Specialized offshore supply vessels like Anchor Handling and Tug Supply (AHTS) vessels are clear examples where risk assessment of the onboard machinery is very important. AHTS are dedicated to support oil rig's movements and towage operations, including anchor handling, towing, supply, and rescue duties. FMEA is important for AHTS vessels as the vessels operate in challenging and hazardous environments where safety is of paramount importance. FMEA also helps to identify failure modes that can impact vessel's operational reliability, and regulatory compliance [2]. In this paper, an enhanced FMEA methodology will be used to assess the possible risks of component failure in the main engine of an AHTS operating off West Africa waters.

This study aligns with and improves upon existing FMEA research that incorporates fuzzy logic and MCDM [3]. Some studies use FAHP alone [4], but lack a ranking method like FTOPSIS. Others apply FTOPSIS alone [5], but without proper weight distribution like FAHP. This study integrates FAHP for weight assignment and FTOPSIS for ranking, combining the strengths of both methods. This ensures more objective and severity-sensitive risk prioritization than traditional RPN or single-method approaches. Also, few studies specifically analyze marine machinery systems using this hybrid FAHP-FTOPSIS approach.

II. METHODOLOGY

Five (5) SMEs with specialized knowledge, practical insights, and ability to evaluate risks within the specific contexts of AHTS vessels are used to conduct FMEA in the main engine system of the AHTS. The main engine information is presented in Table 1. FAHP was used for Severity (S), Occurrence (O), and Detectability (D) weighting, and FTOPSIS for failure modes ranking. A sensitivity analysis was conducted to examine how changes in weight distribution affect failure modes ranking.

2.1 Failure Mode and Effect Analysis (FMEA)

The experts evaluated the failure mode of the different main engine components and assigned numerical ratings for S, O, and D using the scale presented in Table 2. Severity measures the impact of the failure on the system, Occurrence reflects the likelihood of failure occurring, and Detection assesses how easily the failure can be detected before causing significant issues.

The RPN values for each failure mode is calculated using (1).

$$RPN = S \times O \times D \quad (1)$$

TABLE 1. MAIN ENGINE INFORMATION

Total no of M/E	2
Number of Shafts	2
#Port Engine Horsepower	2400 bhp
# Starboard Engine Horsepower	1600 bhp
Starboard # of cylinders	6
Port # of cylinders	8
Rated Engine output	2500hp
Engine rpm	650
Cylinder bore	280mm
Cylinder stroke	360mm
Gearbox Ahead reduction	2.29
Gearbox Astern reduction	2.19

2.2 FAHP

FAHP is an extension of AHP, a structured decision-making methodology developed by Thomas Saaty in the 1970's [6] and used to solve complex decision-making problems by pairwise comparison, where decision-makers compare criteria and alternatives in pairs based on their relative importance. FAHP incorporates fuzzy logic to deal with uncertainty and vagueness in decision-making. Traditional AHP relies on precise numerical values for pairwise comparisons, but in real world situations, human judgement is often imprecise or subjective. FAHP uses fuzzy numbers to represent these uncertainties. The steps for FAHP used in this paper are:

Step 1: define criteria, and alternatives
Step 2: construct fuzzy pairwise comparison matrices using triangular fuzzy numbers in Table 3, to represent pairwise comparison.
Step 3: decision matrix - convert fuzzy numbers into crisp values to
Step 3: normalize matrix and calculate fuzzy weights

2.2 FTOPSIS

FTOPSIS is an extension of the traditional TOPSIS method which incorporates fuzzy set theory that allows for the representation of ambiguous and vague information usually encountered in real-world decision-making problems. TOPSIS is used in evaluating and ranking of alternatives based on how close each of the alternatives are to an imaginary ideal positive and equally how far they are from an imaginary ideal negative solution. The highest ranked and best alternative for the decision maker is one that is closer to the positive ideal solution and further from the ideal negative solution.

To integrate FTOPSIS into FMEA, the traditional crisp values of S, O, and D is replaced with triangular fuzzy numbers (TFNs) using the ten-point scale in Table 4 which allows for finer granularity in rating S, O, and D.

TABLE 2. S,O,D RATING SCALE [11]

Rating	Linguistic term	Occurrence (O) (failure rate measured in operating days)	Severity (S) (failure resulting in hazardous effects)	Likelihood of non-detection (D) by detection system
9	Very high	1 in 3	Engine failure resulting in hazardous effects is very high	Very high chance
7	Moderately high	1 in 20	System performance severely affected	Moderately high
5	Low	1 in 400	Reduced performance with gradual degradation	Low chance
3	Remote	1 in 15,000	Slight effect on system performance.	Remote chance
1	Almost impossible	<1 in 1,500,000	No effect	Almost impossible

TABLE 3: TFN SCALE [6]

Number	Linguistic term	Triangular Fuzzy Numbers
1	Equal importance	(1,1,1)
3	Weak importance	(2,3,4)
5	Strong importance	(4,5,6)
7	Very strong importance	(6,7,8)
9	Absolute importance	(9,9,9)

The steps for FTOPSIS used in this paper are:

Step 1: construct the decision matrix

Step 2: normalize the decision matrix - the values in the decision matrix are normalized using the vector normalisation technique for the r_{ji} element of the normalised decision matrix as follows:

$$r_{ji} = \frac{x_{ji}}{\sqrt{\sum_{j=1}^{N} x_{ji}^2}} \tag{2}$$

where j = 1, 2…, N; i = 1, 2…, k and x_{ji} = alternative j value with respect to criteria i.

TABLE 4: 10-POINT FUZZY SCALE

Crisp Scale	Linguistic Term	TFN
1	Extremely Low	(1,1,2)
2	Very Low	(1,2,3)
3	Low	(2,3,4)
4	Medium Low	(3,4,5)
5	Medium	(4,5,6)
6	Medium High	(5,6,7)
7	High	(6,7,8)
8	Very High	(7,8,9)
9	Extremely High	(8,9,10)
10	Absolutely Critical	(9,10,10)

Step 3: calculate weighted normalized matrix - The next step is to calculate the weighted normalised fuzzy decision matrix u_{ji}. The normalised fuzzy numbers obtained in step 2 are multiplied by the weight values of criteria from 2.1 step 3.

$$u_{ji} = w_i r_{ji} \tag{3}$$

Step 4: Determine Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS) - FPIS and FNIS are determined to evaluate alternatives against the criteria. FPIS represent the best or optimal value for each criterion. These values are determined to create an imaginary alternative that is "most preferred". FNIS represents the worst or least desirable value for each criterion. These values are determined to create an imaginary alternative that is "least preferred "possible values for each criterion.

The imaginary ideal solution i.e., positive (A^+) and negative (A^-) ideal solution respectively are defined as follows:

$$A^+ = \{v_1^+, v_2^+, \dots, v_i^+, \dots, v_k^+\} \tag{4}$$

$$A^- = \{v_1^-, v_2^-, \dots, v_i^-, \dots, v_k^-\} \tag{5}$$

where $v_j^+ \; and \; v_j^-$ represent positive-ideal and negative-ideal values for each criterion j, respectively. $v_j^+ \; and \; v_j^-$ are calculated for each criterion based on whether the criterion is benefit-oriented or cost-oriented.

Step 5: Calculate the distance from FPIS and FNIS - The distance of each alternative from the ideal positive and negative values determines the final ranking of each alternative. Distance from the positive ideal solution S_i^+ and distance from the negative ideal solution S_i^- is gotten from the equation

$$S_i^+ = \sqrt{\sum_{i=1}^{K} \left(v_{ji} - v_i^+\right)^2} \quad (6)$$

where:

v_{ji} is the value of the i-th alternative for the j-th criterion.

$$S_i^- = \sqrt{\sum_{i=1}^{K} \left(v_{ji} - v_i^-\right)^2} \quad (7)$$

where j = 1, 2…, n

Step 6: Calculate the Closeness Coefficient

The overall distance of each alternative A_j from the positive ideal solution is estimated as

$$c_j^+ = \frac{s_j^-}{s_j^+ + s_j^-} \quad (8)$$

Step 7: Rank the Alternatives

The best ranked alternative has the maximum C_j^+ value. This implies that if C_j^+ is close to 1, the ideal alternative is A_j and non-ideal if it is closed to 0.

2.3 Sensitivity Analysis

A sensitivity analysis was conducted to check the impact of criteria weight changes on failure modes.

III. RESULTS

3.1 RPN

From the maintenance records of the AHTS, failure modes of the main engine system that occurred in the past four years were identified, out of which 23 recurring ones were taken for evaluation. These accounted for over 50% of the failure modes within the study period. The following are the failure modes chosen for evaluation:

FM1: Main bearing wear/fatigue
FM2: Main bearing overheating
FM3: Piston ring breakage
FM4: Piston ring excessive wear
FM5: Exhaust valve sticking/seat erosion
FM6: Exhaust valve spring failure
FM7: Cylinder liner worn
FM8: Cylinder liner leakage
FM9: Sea water cooling pump failure
FM10: Sea water cooling pump leakage
FM11: Fuel filter clogged
FM12: Fuel valve nozzle obstructed
FM13: Lube oil filter clogged/blocked
FM14: Lube oil valves and piping leakage, burst flange
FM15: Lube oil cooler reduced cooling capacity
FM16: Lube oil cooler leakage/pipe rupture
FM17: Air intake filter clogged
FM18: Scavenge air duct blocked
FM19: Scavenge air duct leakage
FM20: Gearbox overheating
FM21: Gearbox tooth wear/damage
FM22: Keel cooler fouling
FM23: Keel cooler leak/pipe rupture

The average of the risk criteria (O, S, and D) values for each failure mode assigned by the five experts are presented in Table 5. Through a discussion process, the experts reached a consensus and agreed on the rating of the failure modes, severities, and likelihoods. The RPN values calculated from (1) for each failure mode and their rankings are also presented in Table 5.

3.2 FAHP

The S, O, and D are taken as the criteria with the various failure modes as the alternatives.

Pairwise comparison of the criteria was conducted by the experts, using TFN numbers from Table 3. The pairwise comparison matrix is transformed into crisp values using averaging technique to give the decision matrix, and the results are presented in Table 6.

The fuzzy decision matrix is normalized and the weight of each criterion calculated from the normalized matrix. For example, the weight of S is (0.7389+0.7987+0.5833)/3 = 0.7070. Results are presented in Table 7. From the results, it can be seen that severity is the most critical criterion, followed by occurrence, and detection is the least important.

3.3 FTOPSIS

The S, O, and D values from the five experts (Table 5) are transformed into a fuzzy matrix using TFN numbers from Table 4 to form the fuzzy decision matrix. The matrix is then normalized, and weighted using the weights of S, O, and D from Table 7. The results are presented in Table 8.

Following the steps outline in 2.2 steps 4-8, the FPIS, FNIS, and CC values are calculated, and failure modes ranked. Results are presented in Table 9.

3.4 SENSITIVITY ANALYSIS

In conducting the sensitivity analysis, S was reduced by 20%, while O and D were increased. The new weights of the criteria are as follows: S = 0.5656, O = 0.2859, D = 0.1485. The new rankings of the failure modes are presented in Table 9.

IV. ANALYSIS OF RESULTS

This study applies an improved FMEA method to assess the risks in the main engine system of an AHTS vessel. Instead of relying on the conventional RPN approach, it integrates two fuzzy MCDM techniques. FAHP was used to assign weights to the three FMEA factors: S (0.7070), O (0.2152), and D (0.0778). The weights signify that failures causing severe damage to the engine are prioritized over those that are simple harder to detect.

TABLE 5: RPN AND RANKING

FM	S	O	D	RPN	Ranking
1	8	5	4	160	14
2	9	5	5	225	3
3	9	4	5	180	9
4	8	6	5	240	1
5	5	7	4	140	17
6	6	8	5	240	1
7	5	5	4	100	21
8	7	6	2	84	22
9	9	4	4	144	16
10	7	5	6	210	5
11	6	6	3	108	20
12	5	7	2	70	23
13	8	5	4	160	14
14	6	7	3	126	18
15	7	5	5	175	13
16	9	4	5	180	9
17	6	5	4	120	19
18	7	6	5	210	5
19	6	5	6	180	9
20	9	5	5	225	3
21	7	5	6	210	5
22	6	6	5	180	9
23	8	4	6	192	8

TABLE 6: FUZZY DECISION MATRIX

	S	O	D
S	1	5	7
O	0.2067	1	4
D	0.1467	0.2600	1

TABLE 7: CRITERIA WEIGHTS

	S	O	D	Weight
S	0.7389	0.7987	0.5833	0.7070
O	0.1527	0.1597	0.3333	0.2152
D	0.1084	0.0415	0.0833	0.0778

FTOPSIS was used to rank failure modes based on these weighted factors. By applying FAHP-FTOPSIS, the failure rankings changed significantly compared to conventional RPN calculations and there were three key observations.

First, overheating failures became top priority. Both main bearing overheating (F2) and gearbox overheating (F20) with RPN ranking of 3 were ranked 1 (most critical failure mode) by FTOPSIS. Bearings are crucial for the engine, and overheating can cause catastrophic failure. Also, gearbox overheating can lead to mechanical breakdown, making it just as critical as bearing overheating. The rankings moved up because severity has the highest weight (0.7070), and thus failures with extreme consequences such as overheating leading to system shutdown or damage, become top-ranked.

Second, cooling system failures became more critical. Sea water cooling pump failure (F9) with RPN ranking of 16 was ranked 3 by FTOPSIS. This major shift upwards indicates that cooling system reliability is undervalued by conventional RPN.

Third, some failures were ranked lower. Exhaust valve sticking (F5) with RPN ranking of 17 was ranked 21 by FTOPSIS. This indicates that this is not severe as other failures.

The sensitivity analysis showed the impact of weight changes on failure modes, and thus new rankings. Key observations showed stability in the most critical failures – main bearing overheating (F2) and gearbox overheating (F20) remain the most critical (rank = 1). Despite reducing severity weight, these failures still ranked highest, showing high robustness in risk assessment. Also, failures with moderate severity but high occurrence moved up. For example, piston ring wear (F4) moved from Rank 6 to 3. These failures were previously lower-ranked due to high severity emphasis. With higher weight on occurrence, they now appear more critical. It was also observed that some high-severity failures dropped in importance. For example, lube oil cooler leak (F16) dropped from Rank 4 to 7. These failures had high severity but may have lower occurrence. Their lower rank suggests that they are less frequent, so increasing occurrence weight reduced their importance. Also, failures with low severity and high detection shifted up. For example, fuel filter clogged (F11) remained stable at Rank 17. This suggests that failures with high detectability do not significantly change ranking even when the detection weight is increased.

Based on the differences between traditional RPN and the FAHP-FTOPSIS approach, targeted recommendations can be provided under different operational and decision-making scenarios. It is recommended to use the traditional RPN for quick, straightforward risk assessments where time and computational resources are limited. Also, when failure modes have roughly similar severity, occurrence, and detection ratings (i.e., no major factor dominates). The FAHP-FTOPSIS approach is recommended for critical systems where failure severity outweighs detection difficulty (e.g. turbines, nuclear systems). Also, for failures that can cause cascading effects, since traditional RPN might undervalue high-severity failures with low occurrence.

TABLE 8: FUZZY NORMALIZED WEIGHTED MATRIX

FM	S	O	D
1	0.035	0.009	0.003
2	0.039	0.009	0.004
3	0.039	0.007	0.004
4	0.035	0.010	0.004
5	0.022	0.012	0.003
6	0.026	0.014	0.004
7	0.022	0.009	0.003
8	0.030	0.010	0.001
9	0.039	0.007	0.003
10	0.030	0.009	0.005
11	0.026	0.010	0.002
12	0.022	0.012	0.001
13	0.035	0.009	0.003
14	0.026	0.012	0.002
15	0.030	0.009	0.004
16	0.039	0.007	0.004
17	0.026	0.009	0.003
18	0.030	0.010	0.004
19	0.026	0.009	0.005
20	0.039	0.009	0.004
21	0.030	0.009	0.005
22	0.026	0.010	0.004
23	0.035	0.007	0.005

TABLE 9: FAILURE MODE RANKING

FM	FPIS	FNIS	CC	Old Rank	New Rank
1	0.0072	0.0130	0.6448	7	5
2	0.0061	0.0173	0.7393	1	1
3	0.0077	0.0172	0.6908	4	7
4	0.0063	0.0132	0.6792	6	3
5	0.0177	0.0055	0.2377	21	19
6	0.0133	0.0080	0.3758	15	12
7	0.0184	0.0026	0.1234	23	23
8	0.0094	0.0097	0.5076	10	9
9	0.0074	0.0173	0.6986	3	4
10	0.0108	0.0085	0.4408	13	15
11	0.0136	0.0059	0.3020	17	17
12	0.0175	0.0062	0.2625	19	18
13	0.0072	0.0130	0.6448	7	5
14	0.0132	0.0070	0.3472	16	13
15	0.0106	0.0086	0.4484	12	14
16	0.0077	0.0172	0.6908	4	7
17	0.0143	0.0047	0.2483	20	21
18	0.0098	0.0091	0.4814	11	10
19	0.0146	0.0043	0.2275	22	22
20	0.0061	0.0173	0.7393	1	1
21	0.0108	0.0085	0.4408	13	15
22	0.0138	0.0053	0.2782	18	20
23	0.0091	0.0128	0.5846	9	11

V. CONCLUSION

This study presents a methodological improvement in marine machinery risk assessment by demonstrating that traditional RPN can mis-prioritize failure modes. The FAHP-FTOPS hybrid approach provides more targeted, expert-driven insights, making it ideal for critical, marine machinery systems applications where failure prevention is crucial. The approach is stable and adaptable under different assumptions, making it a reliable decision-making tool for marine machinery risk assessment.

REFERENCES

[1] H. Liu, L. Liu, N. Liu, and L. Mao, “Risk Evaluation in Failure Mode Effect Analysis With Extended VIKOR method under Fuzzy Environment”, Experts System with Applications, vol. 39(17), pp. 12926-12934, 2012.

[2] E. Ibazebo, V. Savsani, A. Siddhpura, and M. Siddhpura, ” Failure Mode and Effect Analysis in the Risk Assessment of the Main Engine System of an Anchor Handling Tug Supply Vessel, ” Proceedings of the ASME 2024 International Mechanical Engineering Congress and Exposition, Portland, Oregon, USA, November 2024.

[3] F. Behnia, H.Z. Ahmadabadi, B. Schuelke-Leech, and M. Mirhassani, “Developing a fuzzy optimized model for selecting a maintenance strategy in the paper industry: An integrated FGP-ANP-FMEA approach,” Expert Systems With Applications, vol. 232, 2023.

[4] R. Fattahi, R. Tavakkoli-Moghaddam, M. Khalilzadeh, N. Shahsavari-Pour, and R. Soltani,” Risk Assessment by a New FMEA Model based on an Extended AHP Method under a Fuzzy Environment,” Environmental Energy and Economic Research, vol. 5(4), pp. 1-14, 2021.

[5] W.R. Magalhães and F.R. Lima-Junior, “A model based on FMEA and Fuzzy TOPSIS for risk prioritization in industrial processes,” Gestão & Produção, vol. 28(4), 2021.

[6] T.L. Saaty, “The Analytic Hierarchy Process”. New York: McGraw Hill, 1980.