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Enhancing the FMEA technique using a combination of Expectation interval, TAGUCHI, MOORA, and geometric mean methods

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ABSTRACT

Risk assessment is a critical component of any maintenance system since the risk of most engineering systems has to be established in order to identify the appropriate maintenance strategy for maintaining it. A commonly used tool in the industry is the Failure Mode and Effect Analysis (FMEA). However, the conventional FMEA makes use of precise information from experts in determining the risk of failure modes, which many experts are averse to, because of the difficulty in determining an exact risk value for the failure mode. The use of an alternative approach that allows the utilisation of both precise and imprecise information becomes imperative. In this paper, two novel risk prioritisation techniques, MOORA-RPN and geometric mean-RPN, are developed for risk prioritisation of failure modes involving imprecise information from experts. Both methods use an expectation interval technique in converting imprecise experts rating into minimum and maximum interval values, while utilising the Taguchi method to produce a different combination of decision criteria minimum and maximum risk values. The MOORA-RPN and geometric mean-RPN use MOORA and geometric mean methods, respectively, for the ranking of the risk of failure modes. The risk prioritisation techniques proposed are compared with a technique in the literature, using a case study of a fuel oil system of a marine diesel engine. The results showed that the proposed techniques with lesser computational effort produce results similar to the mathematical technique in the literature.

Keywords: Failure modes; Taguchi method; MOORA method; geometric mean method; FMEA; decision criteria; alternatives.

INTRODUCTION

Many industries have become moribund due to an inappropriate maintenance system for the maintenance of its asset. There is, therefore, the need for industries to put in place an effective maintenance system for the reliable and safe operation of her plant system for maximum productivity and sustainability. Maintenance strategies are of different types, namely, reactive, time-based preventive and condition-based maintenance. However, the degree of risk of plant system equipment determines the maintenance strategy applicable to it. The subject of risk ranking is, therefore, an important subject that is worthy of analysis.

One of the techniques, popularly applied for risk ranking of failure modes of plant system equipment, is the Failure Mode Effect and Analysis (FMEA). FMEA is a systematic approach that identifies failures of plant system equipment and evaluates the effects using Risk Priority Number (RPN). RPN is the product of the severity of failure (S), its occurrence (O), and degree of detectability of the failure (D). FMEA was developed and applied by the United States Army in 1949 (Scipioni et al., 2002). In the 1970s, the use of the FMEA was extended to the aerospace and aviation industries (Scipioni et al., 2002).

A Team of experts usually assigned values to S, O, and D relying on an ordinal scale; an example is presented in Table 1. The conventional FMEA model is designed to utilise precise data from experts, which many experts are unenthusiastic with (Chin et al. 2009a). Other shortcomings of the technique are (1) the use of only three decision criteria (S, O, and D) and in so doing, neglecting other essential elements such as profitability and environment; and (2) the notion that criteria weights are the same. The first step in the FMEA methodology is the identification of the system/units and components to be investigated. This is followed by the determination of failure modes of the system under investigation. Next, are the identification and listing of causes, effects, and detection methods for each failure modes. Values are then assigned to the severity of failure (S), occurrence (O), and detectability of the failure (D). Finally, RPN is evaluated for each failure mode.

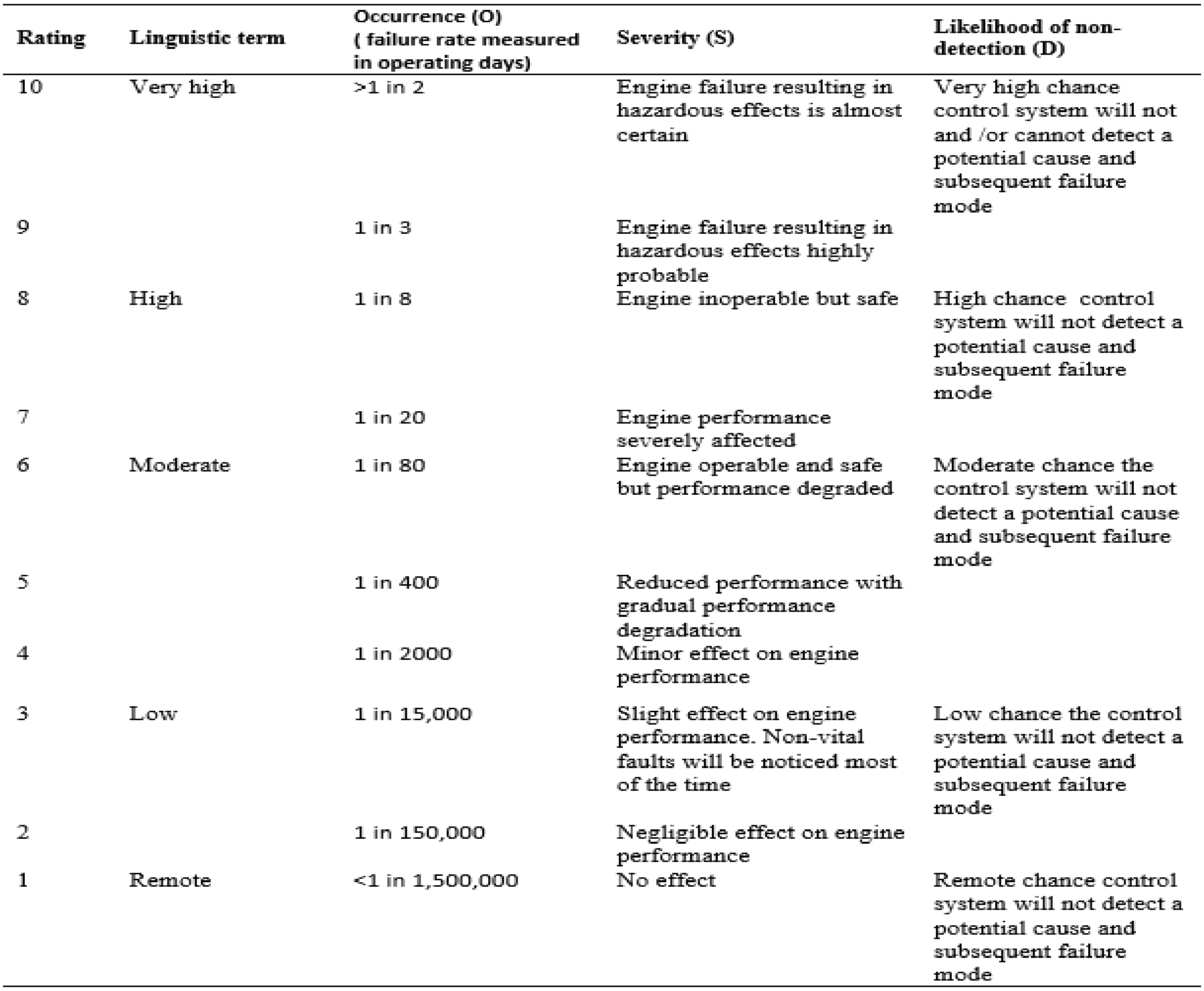
In addressing the limitations of FMEA, different authors have developed alternative approaches while utilising Multi-Criteria Decision Making (MCDM) tools such as AHP and TOPSIS, singly or in combination with one another. Maheswaran and Loganathan (2013) applied a combination of AHP and the Preference Ranking Organisation METHod for Enrichment Evaluation (PROMETHEE) in enhancing the FMEA for better risk ranking. The technique allows the use of more than three decision criteria in the ranking of the risk of failure modes. The technique also allows varying decision criteria weights as opposed to the conventional FMEA, which assume the same weights for each decision criterion. The AHP method was applied to evaluate weights of each decision criterion while applying PROMETHEE for ranking of failure modes. PROMETHEE based technique was also utilised by Ayadi et al. (2013) and Moreira et al. (2009) for the ordering of risk of failure modes. The PROMETHEE technique problem structuring is vague, and as the number of decision criteria increases, the evaluation process complexity increases (Macharis et al., 2004). Furthermore, the technique only uses precise information in the risk decision making the process. However, in real-life application, information from experts may be imprecise, which the above methodologies are incapable of handling.

The problem of aggregating diverse experts' information, which may be imprecise or uncertain, has been investigated by a few authors in recent years. Liu et al. (2012) presented a Fuzzy FMEA based on a mixture of Fuzzy set theory and VIKOR methods. The authors applied linguistic variables to assign a rating for failure modes and weights of decision criteria, while VIKOR was utilised for ranking of the failure modes. In order to overcome the challenges of uncertainty and vagueness from experts' subjective risk rating, Liu et al. (2015) proposed an integrated Fuzzy AHP and entropy methods for decision criteria weights determination while applying Fuzzy VIKOR for the ranking of failure modes. The practical use of Fuzzy technique in the aggregation of imprecise information is cumbersome due to the difficulty in testing and developing extensive sets of fuzzy rules (Zammori and Gabbrielli, 2012). Chin et al. (2009a) developed an enhanced FMEA, which utilises a Data Envelopment Analysis (DEA) approach for analysing imprecise rating from experts. The major challenge with this technique is that the analyst has to be familiar with linear programming and software to effectively use the method, for risk prioritisation. Yang et al. (2011) proposed a modified Dempster-Shafer evidence theory (D-S) in enhancing FMEA. The modified Dempster-Shafer evidence theory (D-S) was used to aggregate the imprecise opinions of experts. The technique was applied for investigating the risk of failure modes of rotor blades of an aircraft turbine. The major limitation of this approach lies in its inability to aggregate differential complete distribution decision criteria rating from different experts. Furthermore, the risk aggregation methodology is sophisticated. Emovon et al. (2014) proposed a technique referred to as AVTOPSIS based on a combination of averaging technique and TOPSIS. The averaging technique was used for aggregating imprecise information from experts while applying TOPSIS technique for ranking of the failure modes. The TOPSIS technique, when compared to other compromise MCDM tools, requires more computational effort in analysing risk (Rao, 2008). Furthermore, according to Opricovic and Tzeng (2004), the relative distance between a positive ideal and negative ideal is not considered in the evaluation process, which seems to affect the output negatively.

From the literature survey, it is evident that there is a need to develop alternative approaches that avoid the limitations of existing techniques. In this paper, two techniques are proposed to complement the existing risk prioritisation approaches while avoiding their limitations and to increase the number of solution techniques the decision-makers can choose. This will support efforts in the literature towards achieving zero machinery failure. The first technique, MOORA-RPN, combines expectation interval with Taguchi, MOORA, and RPN methods, and the second technique, geometric mean-RPN, combines expectation interval, Taguchi, geometric mean, and RPN methods.

In the two techniques, the Expectation interval and Taguchi method are applied for imprecise data aggregation. The ranking of failure modes is performed with MOORA method for the first technique and the geometric mean for the second technique.

Table 1. Ratings for the occurrence (O), severity (S), and Detectability (D) in a fuel oil system (Cicek and Celik, 2013; Pillay and Wang, 2003; Yang et al., 2011) revised.



Rating	Linguistic term	Occurrence (O) (failure rate measured in operating days)	Severity (S)	Likelihood of non-detection (D)
10	Very high	>1 in 2	Engine failure resulting in hazardous effects is almost certain	Very high chance control system will not and /or cannot detect a potential cause and subsequent failure mode
9		1 in 3	Engine failure resulting in hazardous effects highly probable	
8	High	1 in 8	Engine inoperable but safe	High chance control system will not detect a potential cause and subsequent failure mode
7		1 in 20	Engine performance severely affected	
6	Moderate	1 in 80	Engine operable and safe but performance degraded	Moderate chance the control system will not detect a potential cause and subsequent failure mode
5		1 in 400	Reduced performance with gradual performance degradation	
4		1 in 2000	Minor effect on engine performance	
3	Low	1 in 15,000	Slight effect on engine performance. Non-vital faults will be noticed most of the time	Low chance the control system will not detect a potential cause and subsequent failure mode
2		1 in 150,000	Negligible effect on engine performance	
1	Remote	<1 in 1,500,000	No effect	Remote chance control system will not detect a potential cause and subsequent failure mode

METHODOLOGY

Expectation interval

The expectation interval technique is the first stage of imprecise data aggregation in this paper. In this stage, imprecise ratings obtained from experts for failure modes based on decision criteria (O, S and D) expressed as an expectation interval with the maximum and minimum bounds.

The expectation interval steps are as follows:

1. Formation of a confidence decision matrix. The ratings with a confidence level assigned by experts to failure modes based on decision criteria are used to form a confidence decision matrix (m x n), m is the number of failure mode, and n is the number of criteria.

Experts may provide ratings for failure modes in three forms described in Table 2.

Table 2. Types of experts failure modes rating (Chin et al., 2009b).

S/N	Data from experts	Description
1	Precise ratings	Ratings in which experts assign a single value with confidence of 100%. For example, if the rating is 2 this can be written as 2:100%.
2	Complete distribution ratings	Ratings in which experts assign more than one value with confidence summing up to 100%. For example 5:80% and 7:20% are assigned to failure mode it means that a value of 5 at 80% confidence and 7 at 20% confidence with the confidence (80% + 20%) summing to 100%.
3	Incomplete or imprecise ratings	Ratings in which experts assign one or more value with confidence not summing up to 100%. For example, 5:80% is assigned to failure mode with 20% confidence missing. The missing 20% confidence is called local ignorance and could be assigned to any rating between 1 and 10 (Shafer, 1976)

2. Minimum and Maximum risk values computation

The imprecise ratings expressed in the form of a minimum and maximum risk values are computed as follows (Chin et al., 2009a):

$$x_{ij}^{min} = x_{ij}^{1}.q_{ij}^{1} + x_{ij}^{2}.q_{ij}^{2} + \left\{1.\left(100\% - q_{ij}^{1} - q_{ij}^{2}\right)\right\} \quad (1)$$

$$x_{ij}^{max} = x_{ij}^{1}.q_{ij}^{1} + x_{ij}^{2}.q_{ij}^{2} + \left\{10.\left(100\% - q_{ij}^{1} - q_{ij}^{2}\right)\right\} \quad (2)$$

where

x_{ij}^{min} is the minimum risk value of failure mode i with respect to risk criterion j

x_{ij}^{max} is the maximum risk value of failure mode i with respect to risk criterion j

x_{ij}^{1} and x_{ij}^{2} are the ratings assigned by an expert for failure mode i with respect to risk criterion j at percentage confidence q_{ij}^{1} and q_{ij}^{2} respectively.

The data obtained from the expectation interval analysis for each failure mode are generally presented in the form of Table 3.

Table 3. Decision criteria and levels for each failure mode.

Decision criteria	Levels	
	1(min)	2(max)
S	x_{ij}^{min}	x_{ij}^{max}
O	x_{ij}^{min}	x_{ij}^{max}
D	x_{ij}^{min}	x_{ij}^{max}

Min. represents minimum risk (level 1) and max. represents maximum risk (level 2).

TAGUCHI method

Taguchi method was developed by Dr Genishi Taguchi to improve the engineering experimentation process (Viswanathan, 2005). To achieve the objective table referred to, "Orthogonal Array" (OA) was constructed. The use of the Tables made the design of the experiment less cumbersome and more consistent. This is because in the Orthogonal Array approach the most important combinations of factors (decision criteria) are considered as opposed to the full factorial approach, in which all possible combinations for a given set of factors are utilised (Viswanathan, 2005). For example, in designing experiment having three factors P, Q, and R, each having two sets of values (2 levels), 8 experiments will be conducted for full factorial and 4 experiments for the Orthogonal Array approach. The Orthogonal Array (OA) Approach is indicated as (OA) L4 in Table 4.

Table 4. Orthogonal Array (OA) L4 (Viswanathan, 2005).

Experiment	Factors		
	P	Q	R
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

The Orthogonal Array is utilised in this paper for obtaining alternatives combinations of S, O, and D in order to easily obtained different values of Risk Priority Numbers (RPN) for each failure mode. On this basis, Table 4 can then be represented as Table 5.

Table 5. Orthogonal Array (OA) L4 for each failure modes.

Alternatives (Aj)	Decision criteria (Bi)		
	S	O	D
A1	1	1	1
A2	1	2	2
A3	2	1	2
A4	2	2	1

1 and 2 represent two set values (minimum and maximum values) for S, O, and D.

The minimum and maximum values of S, O, and D presented in Table 3 are then fed into Table 5 to produce decision matrix, Z, as shown in Table 6 and a generalised form as Table 7.

Table 6. Decision matrix.

Alternatives (Aj)	Decision criteria (Bi)		
	S	O	D
A1	x_{ij}^{min}	x_{ij}^{min}	x_{ij}^{min}
A2	x_{ij}^{min}	x_{ij}^{max}	x_{ij}^{max}
A3	x_{ij}^{max}	x_{ij}^{min}	x_{ij}^{max}
A4	x_{ij}^{max}	x_{ij}^{max}	x_{ij}^{min}

Table 7. Decision matrix (generalized form).

Alternatives (Aj)	**Decision criteria (Bi)**		
	S	**O**	**D**
A_1	z_{11}	z_{12}	z_{13}
A_2	z_{21}	z_{22}	z_{23}
A_3	z_{31}	z_{32}	z_{33}
-	-	-	-
-	-	-	-
A_m	z_{m1}	z_{m2}	z_{m3}

Note: $z_{11=}\ x_{ij}^{min}$, $z_{12=}\ x_{ij}^{min}$, $z_{13=}\ x_{ij}^{min}$ for row 1

The data in Tables 6 or 7 are used as input into the ranking tools; MOORA and geometric mean to obtain overall risk rating for each failure mode.

Ranking Tools

MOORA method

MOORA is a multi-criteria decision optimisation technique and an acronym for Multi-Objective Optimization based on Ratio Analysis. The technique was introduced by Brauers and Zavadskas (2006) and been used in addressing diverse multi-criteria decision-making problems. Sreeraj (2016) applied MOORA technique for optimisation of resistance spot welding process parameters. Yazdani et al. (2016) used the method for solving material selection decision-making problem. Achebo and Odinikuku (2015) utilised the methodology to optimise parameters of gas metal arc welding. The technique was selected because of the simplicity in application and for the fact that it is hardly affected by weighting technique for decision criteria nor the normalisation method used as opposed to most other methods such as TOPSIS and PROMETHEE (Karande and Chakraborty, 2012).

The steps applicable to the MOORA method are as follows (Yazdani et al. 2016):

(1) Formation of the decision matrix with alternatives, i with respect to criteria, j. An example of such a decision matrix with elements z_{ij} is presented in Table 7.

(2) The normalisation of the decision matrix as follows:

$$f_{ij} = \frac{z_{ij}}{\sqrt{\sum_{i=1}^{m} z_{ij}^2}}\ , \qquad i = 1,2,\dots,m; \quad j = 1,2,\dots,n \tag{3}$$

where f_{ij} is the normalised matrix.

(3) The evaluation of the weighted normalised decision matrix, c_{ij}, as follows:

$$c_{ij} = f_{ij}.w_j \tag{4}$$

where wj denotes the weight of the jth criterion. The weights of criteria can be evaluated using methods such as entropy method.

(4) The evaluation of benefit and cost criteria overall rating for each alternative as follows.

For benefit criteria overall rating

$$Y_i^+ = \sum_{j \in J^{Max}} c_{ij} \tag{5}$$

For cost criteria overall rating

$$Y_i^- = \sum_{j \in J^{Min}} c_{ij} \tag{6}$$

where J^{Max} represents benefit criteria, while J^{Min} represents cost criteria. For the benefits criteria the higher value is more desirable while for the cost criteria the lower values are more desirable.

(5) The overall performance index, Q_i, for each alternative is computed as follows:

$$Q_i = Y_i^+ - Y_i^- \tag{7}$$

The alternatives are ranked with respect to, Q_i, and the higher the value, the better the alternative.

Geometric mean method

In applying the geometric mean method, the first step is to evaluate alternative risks, Ai (RPNi) for each failure mode in the decision matrix (Table 7). This is followed by finding the geometric mean of the alternative risks (RPNi) in order to obtain the overall risk value (FRPN) for each failure mode. The two steps are carried out as follows:

Step 1. Evaluation of alternative risk value for each failure mode as follows:

$$RPN_i = \prod_{j}^{n} z_{ij} \quad , \qquad i = 1,2,\dots,m; \quad j = 1,2,\dots,n \tag{8}$$

Step 2. Computation of overall risk value, $FRPN_j$, of each failure mode as follows:

$$FRPN_j = \left(\prod_{i=1}^{m} RPN_i\right)^{1/m} \quad , \qquad i = 1,2,\dots,m; \quad j = 1,2,\dots,n \tag{9}$$

DATA COLLECTION AND ANALYSIS

Data collection

In order to demonstrate the applicability of the proposed methodologies, a case study of the fuel oil system of a marine diesel engine is utilised. Ten failure modes of the system were identified composing of 2, 1, 2, and 5 failure modes for fuel system pipes, fuel oil circulating pump, fuel oil supply pumps, and fuel valves, respectively, as shown in Table 8. Also presented in Table 8 are the failure causes together with their local and global effects.

To ascertain the risk possessed by each failure mode to the system, three experts reached a consensus and agreed on the ratings presented in Table 9.

Table 8. FMEA for fuel oil system of a marine diesel engine (Emovon, 2016; Cicek et al. 2010; Mokashi, 2002 and Lazakis, 2011).

Equipment items	Failure modes	Failure cause	Local effects	Global effects
Fuel system-pipes, filter	1. pipe leakage/ rupture, sledges in fuel line	deposits, low quality fuel oil	Hot spot , fuel oil spill	Stop engine, fire probable
	2. Clogged fuel filter	Contaminants, Lack of maintenance	Restriction in fuel flow (low fuel pressure), erratic cylinder firing	Engine speed drop, stop engine
Fuel oil circulating pump	3. Low circulating pressure	Suction valve opens too early or late	Engine operates erratically	Reduced engine performance, stop engine
Fuel oil supply pumps	4. Running without oil	Wear-out gear	Low supply pressure	Reduce output from engine
	5. Abnormal sound	Bearing defective/ shaft displacement	Overloading of electric motor	Reduce output from engine
Fuel valve	6. Fuel valve leak	Erosion, deposits	Excessive temperature after individual unit dropped	Reduce output from engine, hot spot
	7. Seizure of injection valve spindle in open position	Control system	Excessive fuel injected into the affected cylinder, high exhaust temperature, black smoke	Reduced engine performance, environmental damage
	8. Clogged fuel valve nozzle	Inadequate maintenance, incorrect fuel temperature, contaminants, poor fuel quality	Insufficient fuel oil for combustion, overloading of some cylinders, excessive smoke,	Reduced engine performance, followed by engine failure
	9. Valve opening prematurely	Low service pressure	Rough running, loss of compression and poor starting	Reduced engine performance
	10. Worn or damage needles and nozzles	Inadequate maintenance, poor quality oil fuel, excessive pressure, erosion	Fuel dribble or poor spray pattern, excessive smoke, poor combustion, excessive exhaust gas temperature, poor starting	Reduced engine performance, engine damage

Table 9. Assigned values by three experts on consensus.

Failure modes	S	O	D
1	7:80%	6	2
2	7:60%	6	2:70%
3	8	5	5
4	8	5	5
5	7	6	4
6	7:60%	5	2:90%
7	9:50%	4:60%	2
8	8:70%	5	2
9	7	6	6
10	8	4	2

The data in Table 9 consist of imprecise and precise ratings of failure mode with respect to decision criteria. For example, 7:80% is an imprecise rating assigned for failure mode 1 with regard to decision criteria, *S*. This is because in this scenario the expert is only 80% certain that the rating is 7. The value of 6 assigned to failure mode 1 with regard to decision criteria, *O*, is a precise rating because the expert is 100% confidence.

Data Analysis

Expectation interval method analysis

Applying Equations 1 and 2, minimum and maximum values of risk of each failure mode based on decision criteria, S, O, and D were obtained. Since the first step in the Taguchi analysis is to arrange the result of the expected interval in the format of Table 5, the result is presented in Table 10.

Table 10. Decision criteria and levels for failure modes 1 to 10.

Failure mode/ Decision criteria	Levels		Failure mode/ Decision criteria	Levels	
	1(min)	2(max)		1(min)	2(max)
Failure mode 1			Failure mode 2		
S	5.8	7.6	S	4.6	8.2
O	6	6	O	6	6
D	2	2	D	1.7	4.4
Failure mode 3			Failure mode 4		
S	8	8	S	8	8
O	5	5	O	5	5
D	5	5	D	5	5
Failure mode 5			Failure mode 6		
S	7	7	S	4.6	8.2
O	6	6	O	5	5
D	4	4	D	1.9	2.8
Failure mode7			Failure mode 8		
S	5	9.5	S	5.9	8.6
O	2.8	6.4	O	5	5
D	2	2	D	2	2
Failure mode 9			Failure mode 10		
S	7	7	S	8	8
O	6	6	O	4	4
D	6	6	D	2	2

Min, represent minimum risk value & Max, represent maximum risk value

Table 10 showed the minimum and maximum risk values obtained for failure modes 1 to 10 using decision criteria information in Table 9 as input data into Equations 1 and 2. There are two categories of values in Table 10. In the first category, the minimum and maximum values of risk are different. For example, in failure mode 1, minimum and maximum risk values with respect to decision criteria, *S*, are 5.8 and 7.6, respectively. This is a result of using imprecise expert ratings as input data into Equations 1 and 2. In the second category, the minimum and maximum values of risk are the same. For example, in failure mode 1, minimum and maximum risk values with respect to decision criteria *O* are 6 and 6, respectively. This is a result of using precise expert rating as input data into Equations 1 and 2.

Taguchi method analysis

The data in Table 10 for each failure mode is then fed into Table 6 to obtain failure modes 1 to 10 orthogonal Array, as presented in Table 11.

Table 11. Orthogonal Array (OA) L4 for failure modes 1to 10.

Failure modes	**Decision criteria**			**Failure modes**	**Decision criteria**		
	S	**O**	**D**		**S**	**O**	**D**
Failure modes 1 alternatives				Failure mode 2 alternatives			
A1	5.8	6	2	A1	4.6	6	1.7
A2	5.8	6	2	A2	4.6	6	4.4
A3	7.6	6	2	A3	8.6	6	4.4
A4	7.6	6	2	A4	8.6	6	1.7
Failure modes 3 alternatives				Failure mode 4 alternatives			
A1	8	5	5	A1	8	5	5
A2	8	5	5	A2	8	5	5
A3	8	5	5	A3	8	5	5
A4	8	5	5	A4	8	5	5
Failure modes 5 alternatives				Failure modes 6 alternatives			
A1	7	6	4	A1	4.6	5	1.9
A2	7	6	4	A2	4.6	5	2.8
A3	7	6	4	3	8.2	5	2.8
A4	7	6	4	4	8.2	5	1.9
Failure modes 7 alternatives				Failure modes 8 alternatives			
A1	5	2.8	2	A1	5.9	5	2
A2	5	6.4	2	A2	5.9	5	2
A3	9.5	2.8	2	A3	8.6	5	2
A4	9.5	6.4	2	A4	8.6	5	2
Failure modes 9 alternatives				Failure modes 10 alternatives			
A1	7	6	6	A1	8	4	2
A2	7	6	6	A2	8	4	2
A3	7	6	6	A3	8	4	2
A4	7	6	6	A4	8	4	2

Table 11 showed four alternatives combination of *S*, *O*, and *D* values (A1 to A4) for failure modes 1 to 10. For example, for failure mode 1, A1 is a combination of minimum value of *S* (5.8), minimum value of *O* (6), and minimum value of *D* (2); A2 is a combination of minimum value of *S* (5.8), maximum value of *O* (6), and maximum value of *D* (2); A3 is a combination of maximum value of *S* (7.6), minimum value of *O* (6), and maximum value of *D* (2); A4 is a combination of maximum value of *S* (7.6), maximum value of *O* (6), and minimum value of *D* (2).

Failure modes ranking

MOORA-RPN method analysis

The data for each failure mode orthogonal array is applied as input data to the MOORA methodology to obtain performance indexes of the different alternatives. The orthogonal array for failure mode 1 is used to demonstrate the MOORA technique application. The data for the orthogonal array for failure mode 1 is normalized firstly using Equation 3 to obtain normalized decision matrix, and the result is shown in Table 12.

Table 12. Normalized decision matrix for failure mode 1.

Alternatives	S	O	D
A1	0.4290	0.5000	0.5000
A2	0.4290	0.5000	0.5000
A3	0.5621	0.5000	0.5000
A4	0.5621	0.5000	0.5000

The weighted normalised matrix was then generated using Equation 4, i.e., by multiplying the normalised matrix in Table 12 with weights of decision criteria and the result being presented in Table 13. The weights of decision criteria used are 0.3526, 0.0745, and 0.5729 for S, O, and D, respectively.

Table 13. Weighted normalised decision matrix for failure mode 1.

Alternatives	S	O	D
A1	0.15126	0.0373	0.2865
A2	0.15126	0.0373	0.2865
A3	0.1982	0.0373	0.2865
A4	0.1982	0.0373	0.2865

This is followed by the computation of benefit and cost criteria by applying Equations 5, and 6 and the results produced are presented in Table 14. Finally, the overall performance index values of each alternative are computed using Equation 7 and the results together with rankings of alternatives are shown in Table 14 and Figure 1. It is worth noting that the ranking of the alternatives was based on the computed MOORA performance index.

Table 14. MOORA performance index and Rank for failure mode 1.

Alternatives	Y+	Y-	Q	Rank
A1	0.4750	0	0.4750	2
A2	0.4750	0	0.4750	2
A3	0.5219	0	0.5219	1
A4	0.5219	0	0.5219	1

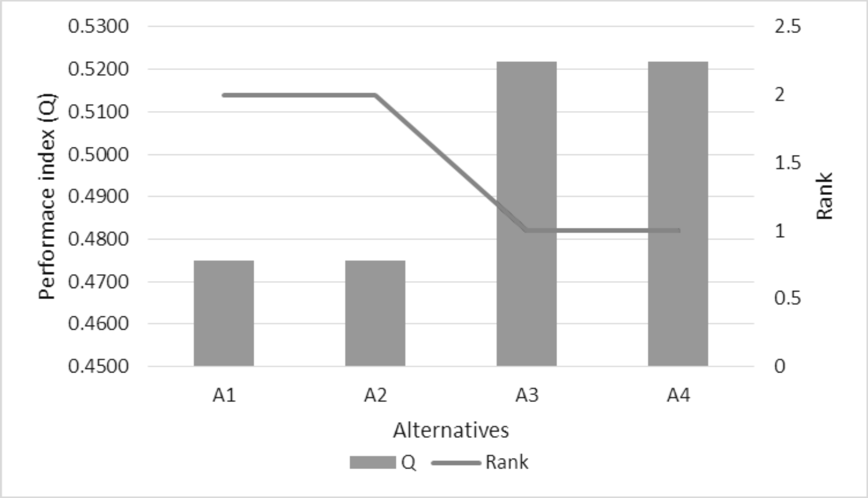


Fig. 1. MOORA performance index, Q, and Rank for failure mode 1.

Following the same methodological steps used for evaluating MOORA performance index values of each alternative risk for failure mode 1, the MOORA performances index values for failure modes 2 to 10 were also computed. The alternative risk of each failure mode was ranked with respect to the computed MOORA performance index values.

The MOORA performance index values for each alternatives risk of failure modes 2, together with the rankings are presented in Table 15 and Figure 2.

Table 15. MOORA performance index and Rank for failure mode 2.

Alternatives	Y+	Y-	Q	Rank
A1	0.3008	0	0.3008	4
A2	0.5327	0	0.5327	2
A3	0.6350	0	0.6350	1
A4	0.4031	0	0.4031	3

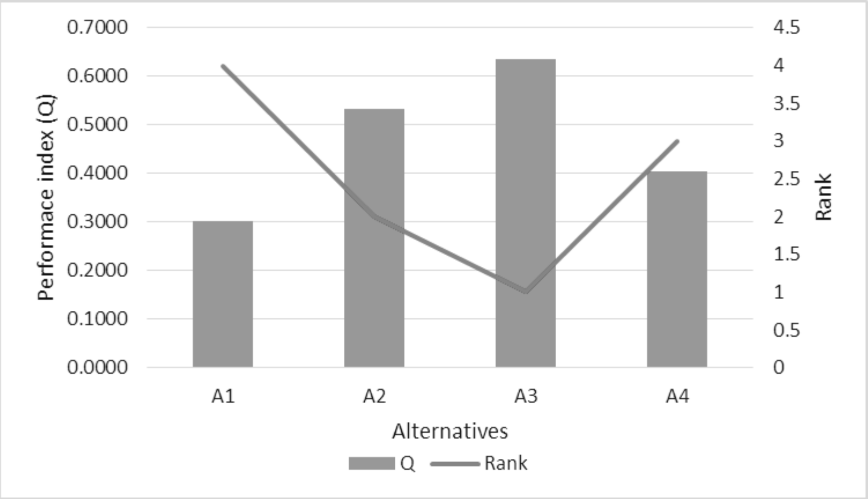


Fig. 2. MOORA performance index, Q, and Rank for failure mode 2.

The evaluated MOORA performance index values for each alternatives risk of failure modes 3, together with the rankings are presented in Table 16 and Figure 3.

Table 16. MOORA performance index and Rank for failure mode 3.

Alternatives	Y+	Y-	Q	Rank
A1	0.5000	0	0.5000	1
A2	0.5000	0	0.5000	1
A3	0.5000	0	0.5000	1
A4	0.5000	0	0.5000	1

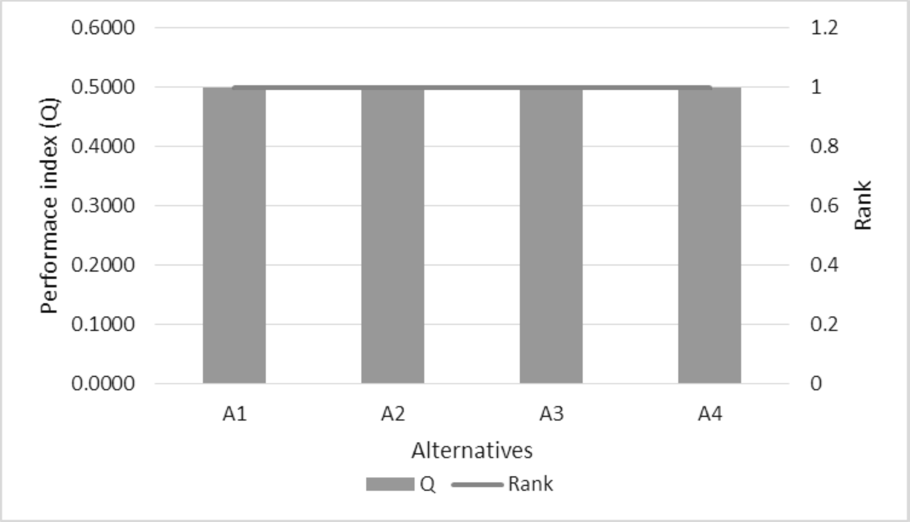


Fig. 3. MOORA performance index, Q, and Rank for failure mode 3.

The computed performance index values together with the rankings for each alternative risk of failure mode 4 to 9 are presented in Tables 17-22 and Figures 4-9, respectively.

Table 17. MOORA performance index and Rank for failure mode 4.

Alternatives	S+	S-	Q	Rank
A1	0.5000	0	0.5000	1
A2	0.5000	0	0.5000	1
A3	0.5000	0	0.5000	1
A4	0.5000	0	0.5000	1

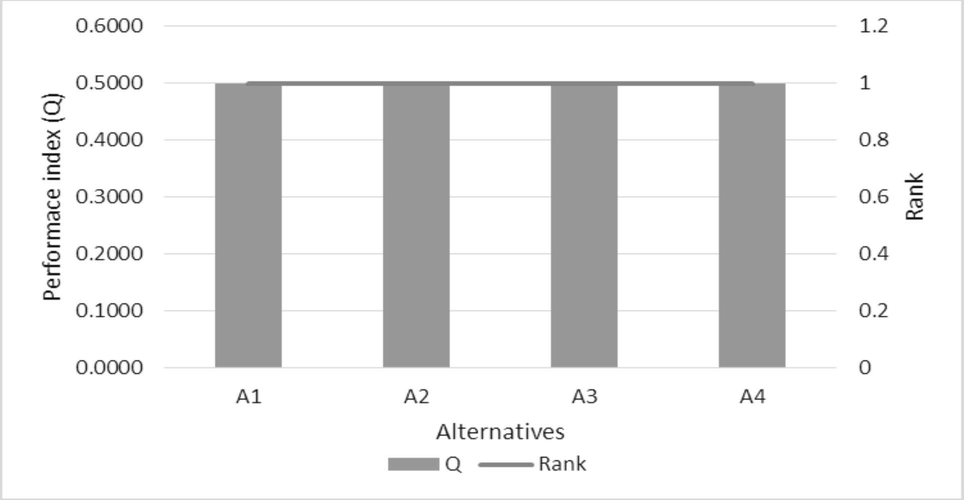


Fig. 4. MOORA performance index and Rank for failure mode 4.

Table 18. MOORA performance index and Rank for failure mode 5.

Alternatives	Y+	Y-	Q	Rank
A1	0.5000	0	0.5000	1
A2	0.5000	0	0.5000	1
A3	0.5000	0	0.5000	1
A4	0.5000	0	0.5000	1

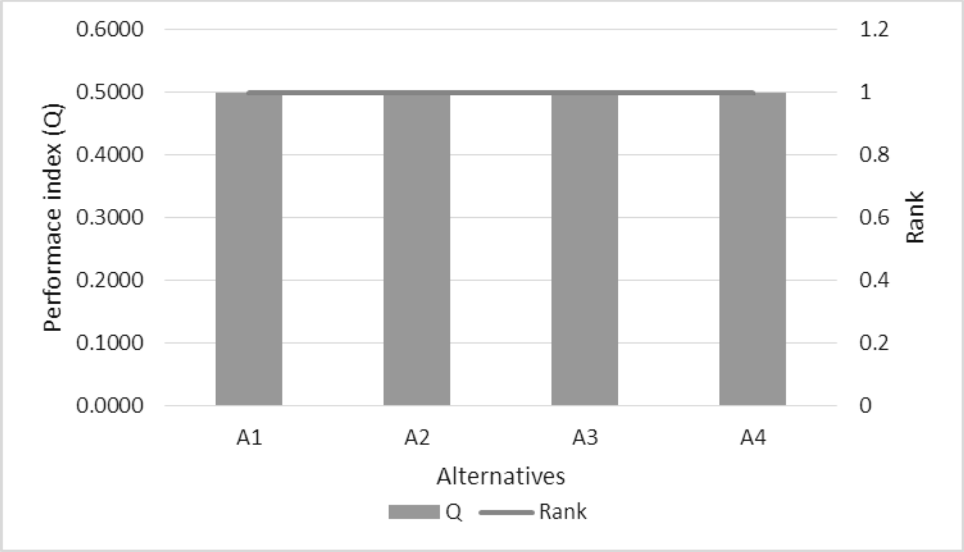


Fig. 5. MOORA performance index and Rank for failure mode 5.

Table 19. MOORA performance index and Rank for failure mode 6.

Alternatives	Y+	Y-	Q	Rank
A1	0.3867	0	0.3867	4
A2	0.4944	0	0.4944	2
A3	0.5899	0	0.5899	1
A4	0.4822	0	0.4822	3

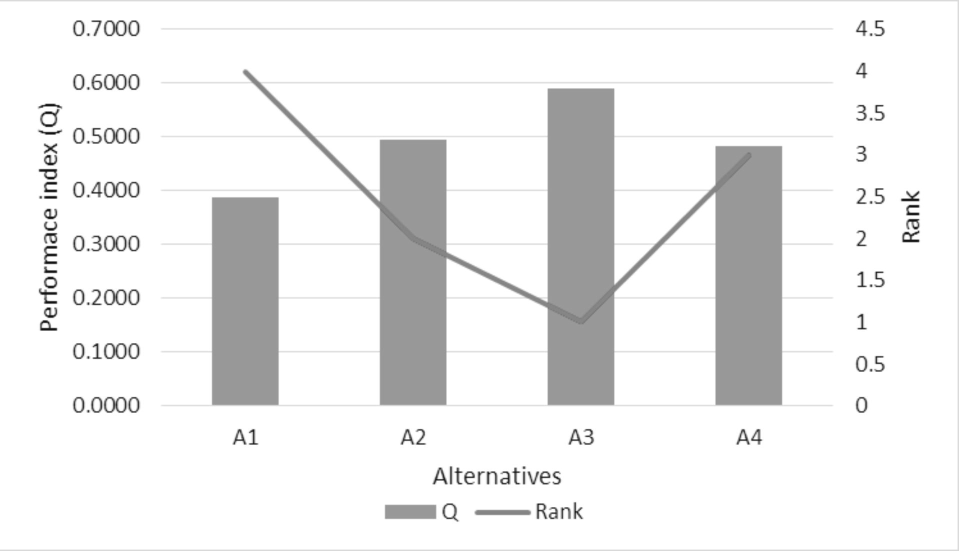


Fig. 6. MOORA performance index and Rank for failure mode 6.

Table 20. MOORA performance index and Rank for failure mode 7.

Alternatives	Y+	Y-	Q	Rank
A1	0.4237	0	0.4237	4
A2	0.4508	0	0.4508	3
A3	0.5282	0	0.5282	2
A4	0.5553	0	0.5553	1

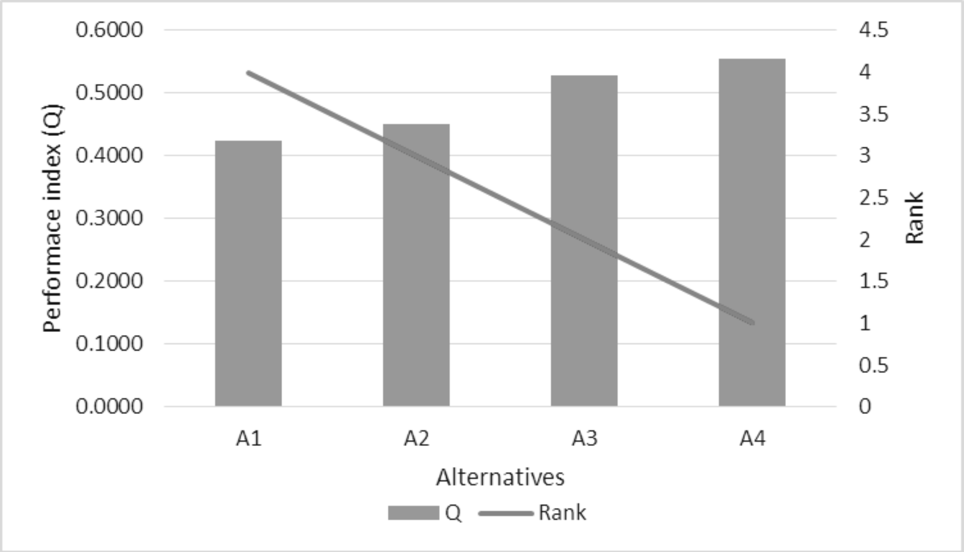


Fig. 7. MOORA performance index and Rank for failure mode 7.

Table 21. MOORA performance index and Rank for failure mode 8.

Alternatives	Y+	Y-	Q	Rank
A1	0.4647	0	0.4647	2
A2	0.4647	0	0.4647	2
A3	0.5293	0	0.5293	1
A4	0.5293	0	0.5293	1

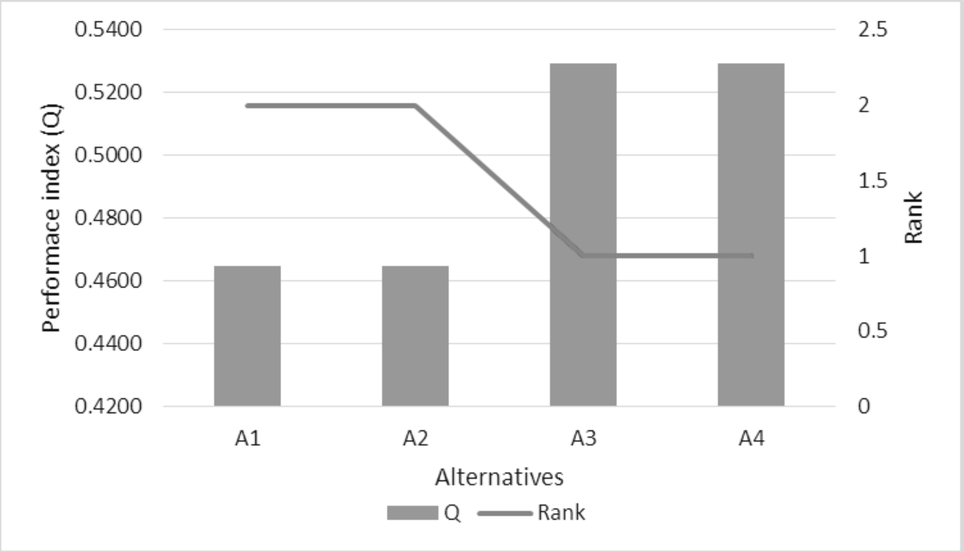


Fig. 8. MOORA performance index and Rank for failure mode 8.

Table 22. MOORA performance index and Rank for failure mode 9.

Alternatives	**Y+**	**Y-**	**Q**	**Rank**
A1	0.5000	0	0.5000	1
A2	0.5000	0	0.5000	1
A3	0.5000	0	0.5000	1
A4	0.5000	0	0.5000	1

Finally, the estimated values of the MOORA performance of each alternative risk of failure mode 10, together with the rankings are indicated in Table 23 and Figure 10.

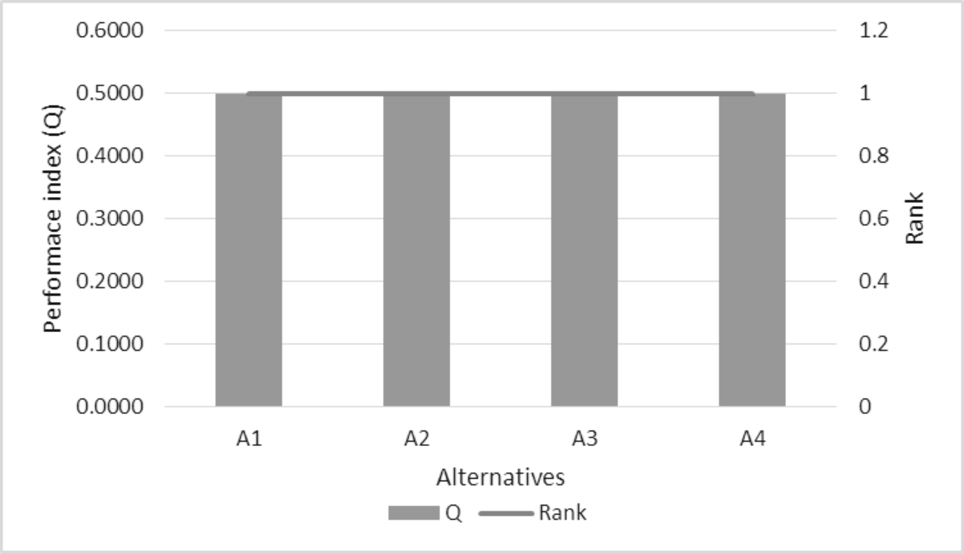


Fig. 9. MOORA performance index and Rank for failure mode 9.

Table 23. MOORA performance index and Rank for failure mode 10.

Alternative	Y+	Y-	Q	Rank
A1	0.5000	0	0.5000	1
A2	0.5000	0	0.5000	1
A3	0.5000	0	0.5000	1
A4	0.5000	0	0.5000	1

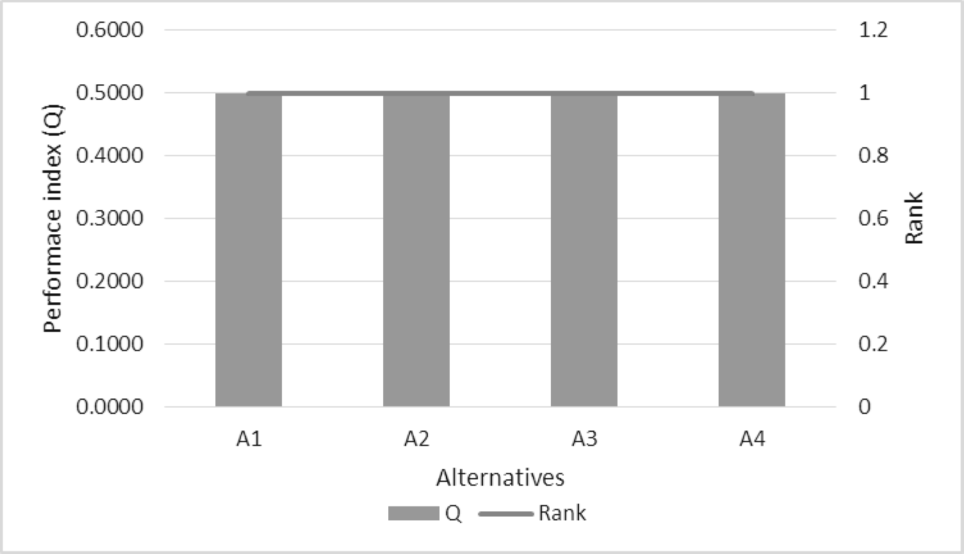


Fig. 10. MOORA performance index and Rank for failure mode 10.

After determining the optimal alternative for each failure mode, the next step is to use the combination of S, O, and D of the optimal alternative to evaluate Risk Priority Number (RPN). For example, the optimal alternatives for failure mode 1 in Table 14 and Figure 1 are A3 or A4 having jointly rank 1 based on MOORA performance index. From Table 11, the values of S, O, and D for A3 or A4 are 7.6, 6, and 2, respectively, and thus the RPN for failure mode 1 is evaluated as follows:

RPN = 7.6* 6 * 2 = 91.2.

Following the same approach, the RPNs for failure mode 2 to 10 were determined, and the RPN values for the ten failure modes and corresponding ranking are shown in Table 24 and Figure 11.

Table 24. MOORA-RPN performance index and Rank for each failure mode.

Failure modes	S	O	D	MOORA-RPN	Rank
1	7.6	6	2	91.2	7
2	8.6	6	4.4	227.04	2
3	8	5	5	200	3
4	8	5	5	200	3
5	7	6	4	168	4
6	8.2	5	2.8	114.8	6
7	9.5	6.4	2	121.6	5
8	8.6	5	2	86	8
9	7	6	6	252	1
10	8	4	2	64	9

From Table 24 and Figure 11, failure mode 9 possesses the highest risk to the fuel oil system of the marine diesel engine having rank 1 among the 10 failure modes. This is followed by failure mode 2 having rank 2 among the 10 failure modes. Failure mode 10, on the other hand, possesses the least threat to the system having rank in the last position. The greatest attention must be given to failure modes 1 and 2 based on this ranking since they possess the greatest danger to the system.

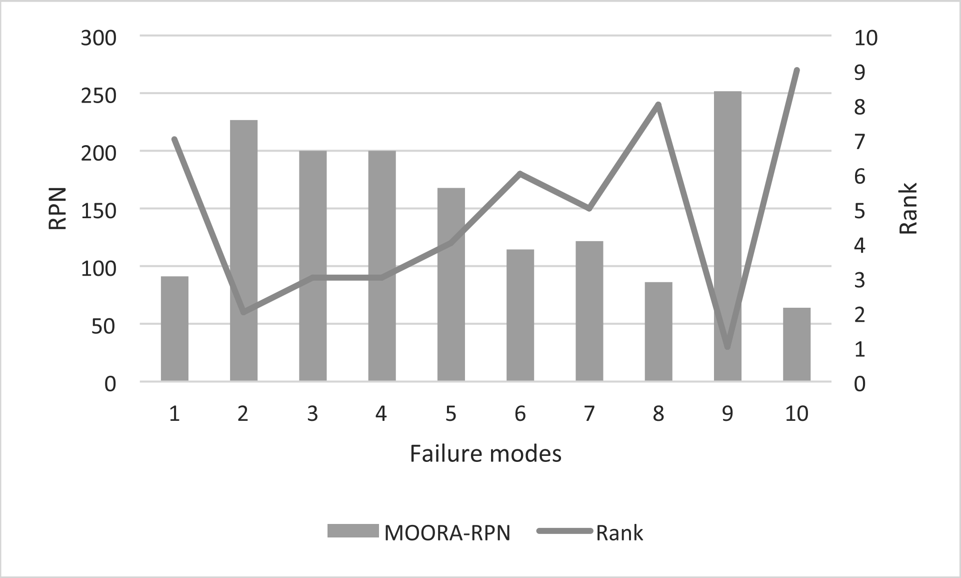


Fig. 11. MOORA-RPN performance index and Rank for each failure mode.

Geometric mean-RPN analysis

The first step in the geometric mean technique is the application of Equation 8 to evaluate the alternatives risk values of each failure mode. This is then followed by using Equation 9 to obtain the geometric mean of the alternatives risks values in order to obtain the overall risk value for each failure mode. The overall risk value obtained and the corresponding rank for each failure mode are shown in Table 25. For example, for failure mode 1, using failure mode 1 data in Table 11 as input data in Equations 8, alternative risk values are obtained as follows:

For Alternative A1, RPN_1 =S* O * D= 5.8 * 6 *2 = 69.6

A2, RPN_2= 5.8 * 6 * 2 =69.6

A3, RPN_3 = 7.6 * 6 *2 = 91.2

A4, RPN_4 = 7.6 * 6 *2 = 91.2

Next Equation 9 is applied to obtain the overall risk value for failure mode 1, i.e., finding the Geometric mean of RPN1, RPN2, RPN3, and RPN4 = 79.67.

The same methodological steps were followed to obtain overall risk value (Geometric mean-RPN) for failure modes 2 to 10 and the results produced are presented in Table 25.

Table 25. Geometric mean-RPN performance index and Rank for each failure mode.

Failure modes	Geometry mean-RPN	Rank
1	79.67	5
2	103.21	4
3	200	2
4	200	2
5	168	3
6	70.82	7
7	58.35	9
8	71.23	6
9	252	1
10	64	8

From Table 25, Failure mode 9 possesses the greatest risk to the fuel oil system of the marine diesel engine while Failure modes 3 and 4 were adjudged second most sensitive failure modes of the system having ranked second, respectively. Failure mode 7 possesses the least threat to the system having rank last among the 10 failure modes.

Comparison of MOORA-RPN and geometric mean-RPN with AVTOPSIS

The two techniques proposed, MOORA-RPN and geometric mean-RPN, are compared with AVTOPSIS previously used by Emovon et al. (2014) in solving a similar problem. For a fair comparison, the AVTOPSIS was applied to solve the case study problem in this paper. The result of the comparative study is shown in Figure 13. From Figure 13, all the techniques revealed that failure mode 9 possesses the highest risk to the fuel oil system of the marine diesel having to rank the first position by the three methods. The geometric mean-RPN method has the same ranking as AVTOPSIS for almost all failure modes except failure modes 7 and 10, which have a difference of one place between failure modes. The MOORA-RPN technique, when compared with AVTOPSIS, shows that the majority of the failure modes have a difference of one place between them. In general, the rankings produced by the three methods are similar, and as such, the proposed technique are valid for ranking of the risk of failure modes of a marine diesel engine and other related engineering systems.

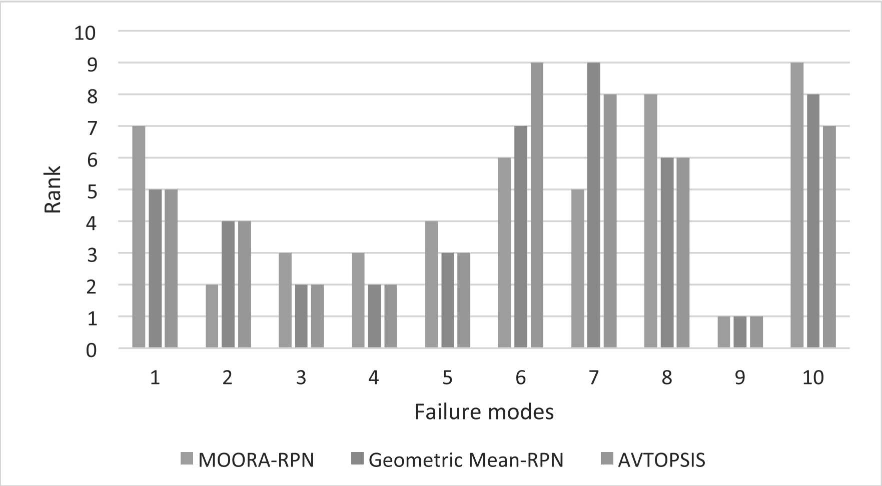


Fig. 13. MOORA-RPN and geometric mean-RPN with AVTOPSIS.

To further validate the proposed techniques, Spearman rank correlation between them and AVTOPSIS was evaluated. Spearman rank correlation coefficient obtained between MOORA-RPN technique and AVTOPSIS, between MOORA-RPN and geometric Mean-RPN, and between geometric mean-RPN and AVTOPSIS is 0.7780, 0.800, and 0.9640, respectively. The close Spearman rank correlation between the two proposed methods and AVTOPSIS from the literature has further revealed that the proposed techniques can effectively be applied as an individual tool for prioritising risk of failure modes of engineering systems while also overcoming the limitations of those methods as discussed in the Introduction Section. In terms of computation effort, the Geometric mean-RPN method requires less effort than the MOORA-RPN method.

CONCLUSION

In this paper, two methodologies for prioritising risk of failure modes of a marine diesel engine and related engineering system are proposed. The two techniques are MOORA-RPN and geometric mean-RPN methods. For the two methods, Taguchi is used in combination with expectation interval method for aggregation of imprecise ratings from experts, which the conventional FMEA is incapable of solving. The MOORA and geometric mean methods were utilised for the ranking of failure modes. From the analysis, the following can be deduced:

- The Taguchi in combination with Expectation interval method is capable of imprecise aggregating ratings from experts,
- The MOORA-RPN method and geometric mean-RPN method produce a similar ranking of failure modes,
- The geometric mean-RPN method is a simpler technique in terms of computational effort requires as it involves two solution steps as opposed to MOORA-RPN with more steps.
- The MOORA-RPN and geometric mean-RPN are viable tools for ranking failure modes as they produce a similar ranking with a similar method in the literature.

Conclusively the two techniques proposed are viable and novel tools capable of addressing the risk of failure modes involving rating from experts that maybe precise or imprecise, thereby completing efforts in the literature toward achieving zero machinery failure.

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تحسين تقنية FMEA باستخدام مجموعة من فترات التوقع، TAGUCHI، MOORA، وطرق المتوسط الهندسي

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الخلاصة

يعتبر تقييم المخاطر عنصراً أساسياً في أي نظام صيانة حيث يجب تحديد مخاطر معظم الأنظمة الهندسية من أجل تحديد استراتيجية الصيانة المناسبة للحفاظ عليها. ومن الأدوات شائعة الاستخدام في هذه الصناعة وضع الفشل وتحليل التأثير (FMEA). ومع ذلك، فإن FMEA التقليدية تستخدم معلومات دقيقة من الخبراء في تحديد مخاطر أنماط الفشل التي يرفضها العديد من الخبراء، بسبب الصعوبة في تحديد القيمة الدقيقة للمخاطر في نمط الفشل. وأصبح استخدام نهج بديل يسمح باستخدام المعلومات الدقيقة وغير الدقيقة أمراً حتمياً. في هذا البحث، تم تطوير طريقتين جديدتين لتحديد المخاطر؛ وهما، MOORA-RPN والوسط الهندسي – RPN من أجل تحديد أولويات المخاطر الخاصة بطرق الفشل التي تتضمن معلومات غير دقيقة من الخبراء. تستخدم كلتا الطريقتين تقنية الفاصل الزمني المتوقع في تحويل تقييم الخبراء غير الدقيق إلى قيم الفواصل الدنيا والقصوى، مع استخدام طريقة Taguchi لإنتاج توليفة مختلفة من قيم المخاطر الدنيا والقصوى لمعايير القرار. يستخدم MOORA-RPN والوسط الهندسي – RPN طرق MOORA والمتوسط الهندسي على التوالي لتصنيف مخاطر أنماط الفشل. تم مقارنة تقنيات تحديد أولويات المخاطر المقترحة بتقنية موجودة في النشرات العلمية، وذلك باستخدام دراسة حالة لنظام زيت الوقود لمحرك الديزل البحري. وأظهرت النتائج أن التقنيات المقترحة ذات الجهد الحسابي الأقل تقدم نتائج مشابهة للتقنية الرياضية في النشرات العلمية.