METHODOLOGY OF USING AN INTEGRATED AVERAGING TECHNIQUE AND MAUT METHOD FOR FAILURE MODE AND EFFECTS ANALYSIS

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ABSTRACT

The conventional Failure Mode and Effects Analysis (FMEA) which is popularly used for prioritizing risk of failure modes of industrial products has limitations such as the inability of the technique to utilize imprecise ratings from experts. These limitations impact negatively on its effectiveness in prioritizing risk. This paper presents a technique that integrates Averaging technique with Multi Attribute Utility Theory method for Failure Mode and Effects Analysis. The objective is to develop an alternative tool that avoids the limitations of the conventional FMEA such that risk of failure mode is prioritized more efficiently. The suitability of the proposed approach is demonstrated with a case study of the rotor blades of an aircraft turbine. The results show that the proposed approach is more flexible and effective for practical application than the conventional FMEA.

***KEYWORDS**: Averaging technique; Multi Attribute Utility Theory; Failure Mode and Effects Analysis; risk criteria*

1.0 INTRODUCTION

Failure Mode Effect and Analysis (FMEA) is one of the most powerful tools for evaluating risk of industrial products such as aircraft engines and ship systems (Pillay & Wang, 2003; Emovon et al., 2014). In such systems, failure occurs in diverse ways and the associated risks and consequences differ. In order to reduce or eliminate failure and associated consequences of these systems, the FMEA offers a useful way to prioritize failure modes. The approach was first developed by NASA in the 1960s as a tool to eliminate or reduce complex system failures in the aviation industry in order for the system to attain high levels of safety and availability (Du, Mo, Deng, Sadiq & Deng, 2014). The conventional FMEA uses Risk Priority Number (RPN) in prioritizing risk of failure modes and is a product of the probability of Occurrence of failure (O), resulting degree of Severity (S) and the ability to Detect (D) the failure before it occurs, and it is expressed as Equation (1):

$$\text{RPN} = OSD \tag{1}$$

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The ordinal scales shown in Tables 1, 2 and 3 are used by experts in assigning values to *O*, *S* and *D* respectively. FMEA application has subsequently been extended to other industries apart from the aviation industry where it originated. For example, Zhou and Shi (2010) presented the application of FMEA for assessment of risk of different equipment items of a large crane vessel's power system. In performing Reliability Centered Maintenance for marine systems, the American Bureau of Shipping (2003) requires FMEA to be employed for determining functions and failures of the systems. Cicek, Turan, Topcu and Searslan (2010) applied FMEA in prioritizing the risk of failure modes of the fuel system of a marine diesel engine. The authors identified 10 failure modes which were ranked using RPN of the FMEA. Cicek and Celik (2013) extended the application of the conventional FMEA to prioritizing the risk of main engine crankcase explosion failures on-board ship. However, despite the wide acceptance of the FMEA in the aviation, marine and other industries, various limitations have affected its effectiveness in prioritizing risk of failure modes of complex industrial products. Some of these limitations are:

i. Inability of the FMEA to aggregate multiple experts' risk ratings that may be imprecise in practical application (Yang, Huang, He, Zhu & Wen, 2011; Su, Deng, Mahadevan & Bao, 2012).
ii. Inability of the technique to utilize more than three risk criteria in prioritizing risk of failure modes, thereby excluding other important criteria such as economic cost and environmental impact (Braglia, 2000, Sachdeva, Kumar & Kumar, 2009, Zammori and Gabbrielli, 2012, Liu et al., 2011).
iii. Different combinations of *O*, *S* and *D* producing same RPN value whereas the risk might be totally different (Sachdeva et al., 2009, Kutlu & Ekmekçioğlu, 2012, Liu, Liu, Liu & Mao, 2012, Sharma & Sharma, 2012).

The purpose of this paper is to develop a systematic approach for prioritizing risk of failure modes that avoids the above limitations of the conventional FMEA. In order to achieve this objective, a novel approach which combines averaging technique with Multi Attribute Utility Theory (MAUT) method is proposed. The averaging technique is designed specifically to aggregate imprecise information from experts and the result is then used as input data into the MAUT methodology in the ranking of the failure modes. The applicability of the integrated Averaging technique and MAUT method is illustrated with a case study of the rotor blades of an aircraft turbine.

Table 1. Ratings for occurrence (*O*)
(Yang et al., 2011, Pillay & Wang, 2003, Cicek & Celik, 2013)

Rating	Probability of occurrence	Possible failure rate
10	Very high (failure is almost unavoidable)	> 1/2
9		1/3
8	High (repeated failures)	1/8
7		1/20
6	Moderate (occasional failures)	1/80
5		1/400
4		1/2000
3	Low (relatively few failures)	1/15000
2		1/150000
1	Remote (failure almost impossible)	< 1/1500000

Table 2. Ratings for severity (*S*)
(Yang et al., 2011, Pillay and Wang, 2003, Cicek and Celik, 2013)

Rating	Effect	Severity of effect
10	Hazardous without warning	Mechanical system failure resulting in hazardous effects almost certain
9	Hazardous with warning	Mechanical system failure resulting in hazardous effects highly probable
8	Very high	Mechanical system inoperable but safe
7	High	Mechanical system performance severely affected
6	Moderate	Mechanical system operable and safe but performance degraded
5	Low	Reduced system performance with gradual performance degradation
4	Very low	Minor effect on mechanical system performance
3	Minor	Mechanical system performance affected slightly.
2	Very minor	Negligible effect on mechanical system performance
1	None	No effect

Table 3. Ratings for Detectability (*D*)
(Yang et al., 2011, Pillay & Wang, 2003, Cicek & Celik, 2013)

Rating	Detection	Criteria
10	Absolutely impossible	System control (detection system) cannot detect a potential cause and subsequent failure mode or there is no system control
9	Very remote	Very remote chance the system control will detect a potential failure cause and consequent failure mode
8	Remote	Remote chance the system control will detect a potential failure cause and consequent failure mode
7	Very low	Very low chance the system control will detect a potential failure cause and consequent failure mode
6	Low	Low chance the system control will detect a potential failure cause and consequent failure mode
5	Moderate	Moderate chance the system control will detect a potential failure cause and consequent failure mode
4	Moderately high	Moderately high chance the system control will detect a potential failure cause and consequent failure mode
3	High	High chance the system control will detect a potential failure cause and consequent failure mode
2	Very high	Very high chance the system control will detect a potential failure cause and consequent failure mode
1	Almost certain	System control will almost certainly detect a potential failure cause and consequent failure mode

2.0 METHODOLOGY

2.1 Averaging Technique

In most practical cases information obtainable from experts is imprecise, which the conventional FMEA is incapable of handling. The averaging technique is principally designed for aggregating imprecise values of individual experts' criteria ratings (*O*, *S* and *D*) such that the imprecisions are captured as an expectation interval (Emovon et al., 2014). The maximum and minimum bounds of the expectation interval are then averaged and used as input into MAUT methodology or any other ranking tool the decision maker deems appropriate to evaluate the risk of each failure mode. The methodological steps of the averaging technique are as follows (Emovon et al., 2014):

STEP 1: Formation of decision problem

Ratings for each failure modes based on decision criteria are obtained from experts and then used to form a decision matrix of alternatives, j, with respect to criteria, i. An example of such a decision matrix with elements x_{ij} is presented in Table 4. The elements x_{ij} may be precise or imprecise (Chin, Wang, Ka Kwai Poon & Yang, 2009a). A rating with single confidence of 100% is referred to as a precise rating. For example, if an expert assigned 5 to a particular failure mode, this can be written as 5:100%. A rating with multiple confidences summing to 100% is known as a complete distribution rating. For example, if an expert assigned 5 at 80% confidence and 7 at 20% confidence, the confidence 80% and 20% sum to 100%.

A rating with confidence not summing to 100% is referred to as incomplete or imprecise distribution. For example, if an expert assigned 7 at 30% confidence and assigned 8 at 60% confidence to a failure mode, there is 10% confidence missing. The 10% confidence missing is generally termed local ignorance and could be assigned to any rating between 1 and 10 (Shafer, 1976).

Table 4. Decision matrix (problem)

Failure modes (A_j)	**Decision criteria (R_i)**		
	O	***S***	***D***
A_1	x_{11}	x_{12}	x_{13}
A_2	x_{21}	x_{22}	x_{23}
A_3	x_{31}	x_{32}	x_{33}
…	…	…	…
A_m	x_{m1}	x_{m2}	x_{m3}

STEP 2: Minimum and maximum risk criteria values computation

The imprecise rating can be denoted as an expectation interval whose minimum and maximum risk values are as expressed in Equations (2) and (3) (Chin, Wang, Poon, & Yang, , 2009b):

$$Min\ x_{ij} = x_{ij}^{1}.z_{ij}^{1} + x_{ij}^{2}.z_{ij}^{2} + \left[1.\left(100\% - z_{ij}^{1} - z_{ij}^{2}\right)\right] \quad (2)$$

$$Max\ x_{ij} = x_{ij}^1 . z_{ij}^1 + x_{ij}^2 . z_{ij}^2 + \left[10.\left(100\% - z_{ij}^1 - z_{ij}^2\right)\right] \quad (3)$$

where $Min\ x_{ij}$ is the minimum risk value
$Max\ x_{ij}$ is the maximum risk value
x_{ij}^1 and x_{ij}^2 are the imprecise rating of failure mode j with respect to risk criterion i assigned by an expert at percentage confidence z_{ij}^1 and z_{ij}^2 respectively.

STEP 3: Computation of the mean risk value

The minimum and maximum risk values are averaged to obtain the mean risk value of failure mode j with respect to risk criterion i as expressed in Equation (4):

$$\overline{x}_{ij} = \frac{Max\ x_{ij} + Min\ x_{ij}}{2} \quad (4)$$

The next step is to use the values of $\overline{x}_{ij}$ to form a decision matrix shown in Table 5 and then evaluate it with the MAUT method.

2.2 MAUT Method

When decision makers are faced with making a decision involving multiple criteria, the MAUT method is one of the Multiple-criteria decision-making MCDM tools utilized in reaching an optimum solution. One of the important features of the technique is the ability of the decision maker to incorporate its risk perception into the decision-making process, which is lacking in other MCDM tools. However, in practical cases, a large amount of data may be required to accurately estimate the risk preference of the decision maker for each decision criterion and the evaluation process might be quite difficult, and to ease the process several assumptions are made. MAUT technique development can be traced to the utility theory developed by Neumann and Morgenstern (1947) and the elicitation and specific assessment techniques developed by Keeney and Raiffa (1976). The MAUT method has been used in the literature in addressing decision-making problems involving multiple criteria. De Almeida and Bohoris (1996) used the methodology in selecting optimum maintenance strategy. Brito and de Almeida (2009) applied the MAUT technique to prioritize the risk of leakage in a natural gas pipeline. Having been applied successfully in solving other multi-criteria problems, the method is combined in this paper with the averaging technique in prioritizing risk of failure modes.

The methodological procedures of the MAUT technique are as follows:

STEP 1: Risk mean values decision matrix formation

The data obtained from Equation (4) is use to form a decision matrix as follows:

Table 5. Risk mean values decision matrix

Failure modes (A_j)	**Decision criteria (R_i)**		
	O	***S***	***D***
A_1	$\overline{x}_{11}$	$\overline{x}_{12}$	$\overline{x}_{13}$
A_2	$\overline{x}_{21}$	$\overline{x}_{22}$	$\overline{x}_{23}$
A_3	$\overline{x}_{31}$	$\overline{x}_{32}$	$\overline{x}_{33}$
…	…	…	…
A_m	$\overline{x}_{m1}$	$\overline{x}_{m2}$	$\overline{x}_{m3}$

STEP 2: Single utility functions determination

The risk preference of the decision maker is incorporated into the risk prioritization process with the utility function. The decision maker's risk perceptions are of three categories risk prone, risk neutral and risk averse. The power series function is a popular utility function used in defining risk criteria and is presented as in Equation (5) (Anders and Vaccaro, 2011):

$$u(R_i) = \frac{(R_i - a)^Y}{(b-a)^Y} \tag{5}$$

where the risk perception of the decision maker is denoted by *Y*.

The value of 1 is assigned when the decision maker is risk neutral. For risk-prone and risk-averse decision makers Y is assigned value greater and less than 1 respectively. The maximum and minimum values of the element of risk criteria R_i are *a* and *b* respectively in Equation (5). Considering Equation (5), the utility values of the elements of risk criteria *O, S* and *D* are evaluated with Equations (6) to (8) respectively:

$$u(O) = \frac{\left(\overline{x}_{1j} - a_1\right)^Y}{(b_1 - a_1)^Y} \tag{6}$$

$$u(S) = \frac{\left(\overline{x}_{2j} - a_2\right)^Y}{(b_2 - a_2)^Y} \tag{7}$$

$$u(D) = \frac{\left(\overline{x}_{3j} - a_3\right)^Y}{(b_3 - a_3)^Y} \tag{8}$$

The maximum and minimum values of the elements that belong to risk criterion *O* are represented as constants a_1, b_1. Constants a_2, b_2 represent the maximum and minimum values of elements of decision criterion *S*. Finally, b_3, a_3 denote the maximum and minimum values of the elements in the decision matrix that belong to the decision *D*.

STEP 3: Multi-attribute utility functions determination

The three decision criteria utility functions *u(O)*, *u(S)* and *u(D)* and their respective weights are combined to form a single analytical model as in Equation (9):

$$U(O,S,D) = w_o u(O) + w_s u(S) + w_D u(D) \quad (9)$$

where w_o, w_s and w_D are the weights of *O*, *S* and *D* respectively.

3.0 RESULTS AND DISCUSSION

To demonstrate the suitability and the potential benefits of the proposed technique, a case study is conducted that examines the rotor blades for an aircraft turbine. The example is adapted from the work of Zhong (2003). Nine failure modes are identified for the turbo rotor blades of the aircraft turbine. For the compressor rotor blades, eight failure modes are identified with varying causes of failure. All together a total of 17 failure modes are identified. The 17 failure modes together with associated causes, effects and failure detection system are presented in Table 6. The failure modes were ranked by three experts using an ordinal scale and considering three risk criteria, *O*, *S* and *D*. Their ratings are presented in Table 7.

Table 6. FMEA for the rotor blades of an aircraft turbine (Zhong, 2003)

S/N	Equipment items	Failure mode	Causes of failure	Effect of failure	Detection system
1	Compressor rotor blades	Deformation	Low yield strength due to improper material treatment, high centrifugal stress due to engine over speed	Blade replacement	Yes
2	Compressor rotor blades	Crack	Improper material	Blade replacement	Yes
3	Compressor rotor blades	Fracture	Corrosion, crack, high local stress	Engine damage, endangered flight safety	No
4	Compressor rotor blades	Corrosion	Imperfect blade surface	Blade replacement	Yes
5	Compressor rotor blades	Blade tip wear	Vertical low-frequency centrifugal load	Blade and engine casing replacement	Yes
6	Compressor rotor blades	Deflection	Low blade strength due to over-temperature	Blade replacement	Yes
7	Compressor rotor blades	Guideway crack	Improper material	Blade replacement	No

8	Compressor rotor blades	Injured by foreign objects	Foreign objects of inhalation of inlet channel	Blade replacement	No
9	Turbo rotor blades	High-cycle intrigue fracture	Torsional resonance caused by design and technology factors	Broke the engine, endangered flight safety	No
10	Turbo rotor blades	Low-cycle intrigue fracture	Low yield strength due to improper material treatment	Engine damage, endangered flight safety	No
11	Turbo rotor blades	Intergranular fracture	Blade over-heating	Engine damage, endangered flight safety	No
12	Turbo rotor blades	Creep-fatigue fracture	Recrystallization of local part of blades	Engine damage, endangered flight safety	No
13	Turbo rotor blades	Fatigue-creep fracture	Surface coating desquamated due to thermal stress	Blade replacement	No
14	Turbo rotor blades	Fracture as a result of a combination of high-cycle and low-cycle fatigue crack	Large gap of blade crown and high vibration stress	Engine damage, endangered flight safety	No
15	Turbo rotor blades	Crack	High thermal stress	Blade replacement	Yes
16	Turbo rotor blades	Corrosion	Loss of corrosion-resistant materials	Blade replacement	Yes
17	Turbo rotor blades	Deformation	Low blade strength due to over-temperature	Blade replacement	Yes

In applying the integrated averaging technique and MAUT method, the first step in addressing the problem in Table 7 is to aggregate the imprecise rating using the averaging technique. The averaging technique was performed firstly by using individual expert imprecise ratings in Table 7 as input into Equations (2) and (3) to obtain individual expert minimum and maximum ratings of failure modes. The minimum and maximum ratings were then averaged using Equation 4 to obtained mean ratings of failure modes, which were used to form the decision matrix shown in Table 8.

Table 7. Three experts' failure mode ratings, adapted from Yang et al. (2011)

Failure modes	Rating of risk factor								
	Expert 1			Expert 2			Expert 3		
	O	***S***	***D***	***O***	***S***	***D***	***O***	***S***	***D***
1	3:40% 4:60%	7	2	3:90% 4:10%	7	2	3:80% 4:20%	7	2
2	2	8	4	2	8:70% 9:30%	4	2	8	4
3	1	10	3	1	10	3	1	10	3
4	1	6:80% 7:20%	3	1	6	3:70% 2:30%	1	6	3
5	1	3	2:50% 1:50%	1	3	1:70% 2:30%	1	3:60% 2:40%	1
6	2	6	5	2	6	5	2	6	5
7	1	7	3	1	7	3	1	7	3
8	3	5:60% 6:40%	1	3	5:80% 6:20%	1	3	5:80% 7:20%	1
9	2:90% 1:10%	10:60% 9:40%	4	2:75% 1:25%	10:90% 9:10%	4	2:80% 1:20%	10:90% 9:10%	4
10	1	10	6	1	10	6	1	10	6
11	1	10	5	1	10	5	1	10	5
12	1	10	6:60% 5:40%	1	10	5:80% 4:20%	1	10	6:70% 5:30%
13	1	10	5:80% 4:20%	1	10	5	1	10	5
14	1	10	6	1	10	6:80% 7:20%	1	10	6
15	2	7:95% 6:5%	3	2	7	3	2	7	3:70% 4:30%
16	2:90% 1:10%	4	3	2:75% 1:25%	4	3	2:80% 1:20%	4	3:80% 2:20%
17	2	5:90% 6:10%	3	2	5:90% 6:10%	3	2	5:60% 6:40%	3

The next step is to apply the MAUT method in evaluating the decision matrix in Table 8 in order to obtain the rank for the 17 failure modes. Three scenarios were studied, the first being when the decision makers are assumed to be risk neutral, the second scenario when they are assumed to be risk prone, and the last scenario when they are assumed to be risk averse.

Table 8. Decision matrix

Failure modes	Expert 1 *O*	Expert 1 *S*	Expert 1 *D*	Expert 2 *O*	Expert 2 *S*	Expert 2 *D*	Expert 3 *O*	Expert 3 *S*	Expert 3 *D*
1	3.6	7	2	3.1	7	2	3.2	7	2
2	2	8	4	4	8.3	4	2	8	4
3	1	10	3	1	10	3	1	10	3
4	1	6.2	3	1	6	2.7	1	6	3
5	1	3	1.5	1	3	1.3	1	2.6	1
6	2	6	5	2	6	5	2	6	5
7	1	7	3	1	7	3	1	7	3
8	3	5.4	1	3	5.2	1	3	5.4	1
9	1.9	9.6	4	1.8	9.6	4	1.8	9.9	4
10	1	10	6	1	10	6	1	10	6
11	1	10	5	1	10	5	1	10	5
12	1	10	5.6	1	10	4.8	1	10	5.7
13	1	10	4.8	1	10	5	1	10	5
14	1	10	6	1	10	6.2	1	10	6
15	2	7	3	2	7	3	2	7	3.3
16	1.9	4	3	1.8	4	3	1.8	4	2.8
17	2	5.1	3	2	5.1	3	2	5.4	3

The decision makers are three experts who rated failure modes with respect to risk criteria. In applying the MAUT method, the first step was to evaluate the utility function values of elements of criteria *O*, *S* and *D* by applying Equations (6) to (8) respectively to the individual experts' mean ratings of failure modes in Table 8. The utility function values of the three risk criteria *O*, *S* and *D* together with decision criteria weights are aggregated using Equation (9) to obtain MAUT utility values for each failure mode. The MAUT utility values (multi-attribute utility functions values) and corresponding rankings obtained for the 17 failure modes in the three scenarios – risk neutral (Y=1), risk prone (Y=2) and risk averse (Y=0.5) – are presented in Tables 9 to 11.

From Tables 9 to 11, columns 2 to 4 represent the MAUT utility values obtained for the 17 failure modes using data from experts 1 to 3 as input into the MAUT methodology whilst their corresponding rankings are presented in columns 6 to 8. The overall ranking of the failure modes is the mean values in column 5, which are the averages of experts 1 to 3's MAUT utility values in columns 2 to 4 and the corresponding ranking presented in column 9.

Table 9. MAUT overall ranking of failure modes (Y=1)

Failure modes	MAUT utility values				Ranking			
	Expert 1	**Expert 2**	**Expert 3**	**Mean**	**Expert 1**	**Expert 2**	**Expert 3**	**Mean**
1	0.6714	0.5345	0.6784	0.6281	1	5	1	2
2	0.5374	0.8214	0.5735	0.6441	5	1	3	1
3	0.4000	0.3962	0.4000	0.3987	12	11	13	12
4	0.2371	0.2103	0.2378	0.2284	16	16	16	16
5	0.0250	0.0144	0.0000	0.0131	17	17	17	17
6	0.5016	0.4709	0.5424	0.5050	7	9	6	7
7	0.2714	0.2676	0.2784	0.2725	15	14	15	15
8	0.4490	0.3943	0.5226	0.4553	10	12	8	10
9	0.5886	0.5471	0.6096	0.5818	2	3	2	3
10	0.5500	0.5404	0.5500	0.5468	3	4	4	5
11	0.5000	0.4923	0.5000	0.4974	8	6	9	8
12	0.5300	0.4827	0.5350	0.5159	6	8	7	6
13	0.4900	0.4923	0.5000	0.4941	9	6	9	9
14	0.5500	0.5500	0.5500	0.5500	3	2	4	4
15	0.4445	0.4176	0.4979	0.4533	11	10	11	11
16	0.2986	0.2590	0.3104	0.2893	14	15	14	14
17	0.3631	0.3362	0.4181	0.3725	13	13	12	13

Table 10. MAUT overall ranking of failure modes (Y=2)

Failure modes	MAUT utility values				Ranking			
	Expert 1	**Expert 2**	**Expert 3**	**Mean**	**Expert 1**	**Expert 2**	**Expert 3**	**Mean**
1	0.5580	0.3277	0.5661	0.4839	1	9	1	4
2	0.3096	0.7052	0.3427	0.4525	9	1	9	6
3	0.3400	0.3370	0.3400	0.3390	8	8	10	9
4	0.1027	0.0818	0.1033	0.0959	15	15	15	15
5	0.0025	0.0008	0.0000	0.0011	17	17	17	17
6	0.2817	0.2530	0.3163	0.2837	11	10	11	11
7	0.1380	0.1349	0.1461	0.1397	13	13	14	14
8	0.3015	0.2296	0.4149	0.3153	10	11	8	10
9	0.4106	0.3819	0.4415	0.4113	7	7	7	8
10	0.5500	0.5311	0.5500	0.5437	2	3	2	2
11	0.4600	0.4479	0.4600	0.4560	5	4	5	5
12	0.5116	0.4335	0.5209	0.4887	4	6	4	3
13	0.4444	0.4479	0.4600	0.4508	6	4	5	7
14	0.5500	0.5500	0.5500	0.5500	2	2	2	1
15	0.2045	0.1849	0.2519	0.2138	12	12	12	12
16	0.1000	0.0751	0.1026	0.0926	16	16	16	16
17	0.1336	0.1140	0.1759	0.1412	14	14	13	13

Table 11. MAUT overall ranking of failure modes (Y=0.5)

Failure modes	MAUT utility values				Ranking			
	Expert 1	**Expert 2**	**Expert 3**	**Mean**	**Expert 1**	**Expert 2**	**Expert 3**	**Mean**
1	0.7886	0.7129	0.7931	0.7649	1	3	1	2
2	0.7263	0.9009	0.7533	0.7935	3	1	3	1
3	0.4581	0.4550	0.4581	0.4571	14	14	14	14
4	0.3610	0.3393	0.3615	0.3539	16	16	16	16
5	0.0791	0.0600	0.0000	0.0464	17	17	17	17
6	0.6991	0.6755	0.7303	0.7016	4	4	4	4
7	0.3849	0.3818	0.3894	0.3854	15	15	15	15
8	0.5703	0.5356	0.6136	0.5732	7	9	7	7
9	0.7497	0.7136	0.7630	0.7421	2	2	2	3
10	0.5500	0.5451	0.5500	0.5484	8	8	9	9
11	0.5236	0.5193	0.5236	0.5222	12	10	12	12
12	0.5398	0.5137	0.5424	0.5320	10	12	11	10
13	0.5179	0.5193	0.5236	0.5203	13	10	12	13
14	0.5500	0.5500	0.5500	0.5500	8	7	9	8
15	0.6640	0.6416	0.7043	0.6700	5	5	5	5
16	0.5363	0.5008	0.5518	0.5296	11	13	8	11
17	0.6015	0.5792	0.6460	0.6089	6	6	6	6

In Table 9, where the decision makers are assumed to be risk neutral, the failure mode 2 is ranked first, having the highest MAUT utility value of 0.6441. This is followed by failure mode 1, occupying the second position. The lowest rank is for failure mode 5, which has the lowest MAUT utility value of 0.0131. In Table 10, where decision makers are assumed to be risk prone, failure mode 14 is ranked first, having the highest MAUT utility value of 0.5500. This is followed by failure mode 10, occupying the second position with a MAUT utility value of 0.5437. Failure mode 5 is occupying the last position, having the lowest MAUT utility value. In Table 11, where decision makers are assumed to be risk averse, the first position is occupied by failure mode 2, having the highest MAUT utility value of 0.7935, while the lowest ranked is failure mode 5, with the lowest MAUT utility value of 0.0464.

It is obvious from the results that the risk perception of the decision makers is a strong factor in the risk prioritization process, as the result produced from risk-prone decision makers differs significantly from that of risk-neutral and risk-averse decision makers. However, there is no significant difference between rankings of failure modes obtained by the MAUT method when decision makers are risk prone and risk neutral, as all the 17 failure modes are ranked almost completely the same.

The proposed method is compared with the results obtained from the conventional FMEA (RPN) to see the similarity between the two methods. Ordinarily, the RPN methodology is incapable of utilizing imprecise information from experts; as a result, the aggregated imprecise ratings from experts using the averaging technique is used as input into the RPN and the results obtained are presented in Table 12.

Table 12. RPN ranking of failure modes

Failure modes	RPN values				Ranks			
	Expert 1	**Expert 2**	**Expert 3**	**Mean**	**Expert 1**	**Expert 2**	**Expert 3**	**Mean**
1	50.40	43.40	44.80	46.20	7	9	10	9
2	64.00	132.80	64.00	86.93	2	1	2	1
3	30.00	30.00	30.00	30.00	12	12	12	12
4	18.60	16.20	18.00	17.60	15	15	15	15
5	4.50	3.90	2.600	3.67	17	17	17	17
6	60.00	60.00	60.00	60.00	3	4	3	4
7	21.00	21.00	21.00	21.00	14	14	13	14
8	16.20	15.60	16.20	16.00	16	16	16	16
9	72.96	69.12	71.28	71.12	1	2	1	2
10	60.00	60.00	60.00	60.00	3	4	3	4
11	50.00	50.00	50.00	50.00	8	6	7	7
12	56.00	48.00	57.00	53.67	6	8	6	6
13	48.00	50.00	50.00	49.33	9	6	7	8
14	60.00	62.00	60.00	60.67	3	3	3	3
15	42.00	42.00	46.20	43.40	10	10	9	10
16	22.80	21.60	20.16	21.52	13	13	14	13
17	30.60	30.60	32.40	31.20	11	11	11	11

Firstly, the results obtained from the MAUT method when decision makers are assumed to be risk neutral (Table 9, column 9) are compared with the results obtained from the conventional FMEA (Table 12 column 9). Failure mode 2 was ranked number 1 by the two methods in this scenario and as such is the most significant failure mode among the 17 failure modes. The failure mode that was ranked as the worst one by the two techniques is failure mode 5, occupying position 17 among the 17 failure modes. This shows that there is similarity in the results produced by the two methods, and as such validated the proposed technique. However, looking at the results generated by the MAUT method (Table 10, column 9) when the decision makers are assumed to be risk prone when compared with the output of RPN (Table 9, column 9), there appears to be a significant difference between them. For example, in the MAUT method, failure mode 14 is ranked number 1 while, in the RPN method, failure mode 2 is ranked number 1; failure mode 1 is ranked number 4 by the MAUT method and failure mode 1 is ranked number 9 by the RPN method.

4.0 CONCLUSION

This paper has proposed a systematic approach that combines the averaging technique with the MAUT method. The averaging technique is used in aggregating imprecise information from experts while the MAUT technique is applied in the ranking of failure modes. One of the unique features of the proposed method is the incorporation of the risk perception of the decision makers into the risk prioritization process, which is lacking in the conventional FMEA. Other important features of the proposed approach that are deficient in the conventional FMEA are: (1) the ability to incorporate more than three decision criteria and (2) the ability to utilize imprecise rating from experts. A case study of an aircraft turbine rotor blade was used to demonstrate the suitability of the proposed technique. The results revealed that decision makers risk perception impact significantly in the decision-making process and that the proposed method is capable of solving the risk prioritization problem effectively whilst avoiding the limitations of the conventional FMEA. Although the method was applied in this paper in solving the risk prioritization problem of an aircraft turbine rotor blade, the technique is capable of addressing other machinery FMEA problems.

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