FAILURE MODE AND EFFECTS ANALYSIS OF SHIP SYSTEMS USING AN INTEGRATED DEMPSTER SHAFER THEORY AND ELECTRE METHOD

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ABSTRACT: Failure Mode and Effects Analysis (FMEA) is a risk analysis tool which is used to define, identify, and eliminate known and/or potential failures from a system. The task is generally performed by a team of experts. Each of the team of experts can express diverse opinions in rating of failure modes of systems which may be in the form of precise data and imprecise distribution ratings. However the RPN of FMEA is incapable of using these various forms of information in the prioritisation of risk of failure modes. This is one of the main limitations of FMEA. Furthermore the technique is limited to the use of three decision criteria thereby excluding other important decision criteria such as production loss in prioritising risk. To address these problems a novel FMEA tool was proposed which combines Dempster Shafer Theory with the ELECTRE method to provide a more efficient failure mode prioritisation method. The Dempster Shafer Theory was used in aggregating different failure mode ratings from experts and the ELECTRE method was applied in the ranking of failure modes. The applicability of the proposed technique was demonstrated with a case study of a marine diesel engine. The results showed that the proposed method could be applied in addressing risk prioritisation problem more efficiently than the FMEA and its variants.

KEYWORDS: *Dempster Shafer Theory, ELECTRE method, FMEA, ship system.*

1.0 INTRODUCTION

Ship system operation requires high levels of safety and reliability and these can only be accomplished by having an effective maintenance system in place. Basically, maintenance system consists of three major elements that must perform optimally in order to attain high level of the ship system safety and reliability. The three main elements of maintenance management system are risk assessment, maintenance strategy selection and maintenance task interval determination. The focus in this paper is the risk assessment component and it is very central to the operation and maintenance of ship system because the maintenance task to be performed on each of the equipment item of the system is a function of the assessed risk. Failure Mode Effect and

Analysis (FMEA) is one of the most popular and powerful tools for assessing risk of ship systems [1, 2]. The technique was first proposed by NASA in the 1960s as a tool to identify and eliminate complex system failures in order for the system to achieve desirable levels of safety and reliability [3]. In analysing risk, FMEA puts into consideration how equipment items fail, the effect of an individual failure on the entire system and possible means of failure detection. Traditionally, FMEA uses Risk Priority Number (RPN) in evaluating and prioritising risk. FMEA is defined as the product of three risk criteria; probability of Occurrence (O), resulting level of Severity (S) and the inverse of the ability to Detect (D) the failure before it occurs. In assigning values to these three risk decision criteria an ordinal scale of 1-10 is generally applied by most researchers and industries [1,4,5]. Despite the popularity of the FMEA it has some limitations which has affected the efficiency of the tool in prioritising the risk of failure modes of most complex system of which the ship system is not excluded. Some of these limitations are: (1) the inability of the tool to utilise more than three decision criteria in prioritising risk of failure mode (2) the inability of the tool to consider the relative importance of decision criteria in the risk decision making process (3) the inability of the technique to utilise imprecise information from experts and (4) the questionable and debatable mathematical formula use in aggregating risk criteria[4, 6].

To overcome the limitations of the traditional FMEA, different techniques based on the Multi-Criteria Decision Making (MCDM) have been developed in literature. Braglia [7] presents a technique based on Analytical Hierarchy Process (AHP). The AHP is used as an alternative to the RPN in aggregating four risk criteria; O, S, D and expected cost, for the prioritisation of causes of failure for an Italian refrigerator manufacturing firm. Zammori and Gabbrielli [8] propose Analytical Network Process (ANP) approach for prioritising failures in FMEA system. The authors consider three risk criteria, O, S and D in prioritising risk of failure mode. The use of the ANP allows the interrelationship between risk criteria to be considered in the decision making process. Maheswaran and Loganathan [9] present a methodology based on Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE as an alternative for the RPN used in the traditional FMEA, for ranking risk of failure modes of a boiler system.

All of the aforementioned papers have improved the efficiency of the traditional FMEA system, as it is possible to utilise more than three decision criteria in the ranking of risk of failure mode. Furthermore, the risk of different failure modes is better distinguished with various MCDM tools than the RPN of the FMEA system. However, the MCDM tools applied increases the evaluation process complexity as the number of decision criteria increases. Furthermore, the techniques only allow the use of precise information from the experts in the decision making process whereas in real life situation the data may be precise or imprecise or a combination of both.

There is a need to develop a more systematic approach for prioritising risk of failure modes of ship systems. In order to overcome the challenges of the traditional FMEA and its variants in literature this study proposed a novel FMEA tool which combined Dempster Shafer Theory with the ELECTRE method. The Dempster Shafer theory technique was applied in aggregating different assessment which may be precise or imprecise from the experts that make up the FMEA team. The ELECTRE method is applied in the ranking of risk of failure modes of the ship system.

2.0 METHODOLOGY

2.1 Dempster Shafer Combination theory

The origin of Dempster Shafer Theory (DST) can be traced to Dempster [10] who develops the theory of upper and lower probabilities and Shafer [11] who further improves on the technique. The tool has been used in different fields in modelling and aggregating empirical evidence in individual's mind. DST has been integrated with the RCM logic tree in the selection of optimum maintenance strategy for different complex systems [12]. The technique has been applied in solving data inconsistency in reliability decision problem. Due to its remarkable success in addressing problem of data uncertainty in different domain, it is combined with the ELECTRE method in this paper to address the problem of data imprecision in risk prioritisation problem of ship system. The basics of the DST are presented in this section and are as follows [12, 13]:

Let be a finite set of mutually exclusive and exhaustive hypothesis. The set generally refers to the frame of discernment. A function m(Y) is defined as the Basic Belief Assignment (BBA) if the following conditions are satisfied.

$$m:2 \rightarrow [0,1]$$

$$\mathrm{m}(\emptyset) = 0$$

$$\sum_{A\subset} m(Y) = 1$$

A new BBA, *m*(C), can be formed from the combination of two BBAs $m_1(Y)$ and $m_2(Z)$ (*Y* and *Z* belong to set ◎), as follows:

$$m(C) \blacksquare m_1(Y) \oplus m_2(Z) \blacksquare \begin{cases} \dfrac{\sum_{Y\cap Z \blacksquare y} m_1(Y)m_2(Z)}{1-k} & y \not\blacksquare \emptyset \\ 0 & y \blacksquare \emptyset \end{cases} \tag{1}$$

But

$$k \blacksquare \sum_{Y\cap Z \blacksquare \emptyset} m_1(Y)m_2(Z)$$

which denotes the degree of conflict between two bodies of evidence, Y and Z.

The application of this combination rule for aggregating different opinions of experts as it concerns risk of failure modes prioritisation is described as follows [4, 6].

◎ = [1,2,3,4,5,6,7,8,9,10] i.e. ordinal scale 1 to 10 rating for risk decision criteria; *m*(*Y)* represents the probability rating given by experts which support proposition *Y*. *Y* is the specific value from the set ◎ to a decision criterion.

Example: The criterion D, rated by two experts for failure mode 1 in Table 3 is used to demonstrate the Dempster Shafer Theory combination rule application. From Table 3, the risk rating of criterion D, by expert 1 is 4:70% and 3:30% and that of expert 2 is 4:40% and 5:60%.

The discernment frame for this problem is formed as = [3, 4, 5] and the BBAs is as follows:

$$m_1(3) = 0.3,\ m_1(4) = 0.7,\ m_2(4) = 0.4 \text{ and } m_2(5) = 0.6$$

$$m_{12}(3) = m_1(Y) \oplus m_2(Z) = \frac{\sum_{Y\cap Z=3} m_1(Y)m_2(Z)}{1 - \sum_{Y\cap Z=\emptyset} m_1(Y)m_2(Z)} = \frac{0}{1 - 0.12 + 0.18 + 0.42}$$
$$= 0$$

$$m_{12}(4) = m_1(Y) \oplus m_2(Z) = \frac{\sum_{Y\cap Z=4} m_1(Y)m_2(Z)}{1 - \sum_{Y\cap Z=\emptyset} m_1(Y)m_2(Z)} = \frac{0.7 \, x \, 0.4}{1 - 0.12 + 0.18 + 0.42}$$
$$= 1$$

$$m_{12}(5) = m_1(Y) \oplus m_2(Z) = \frac{\sum_{Y\cap Z=3} m_1(Y)m_2(Z)}{1 - \sum_{Y\cap Z=\emptyset} m_1(Y)m_2(Z)} = \frac{0}{1 - 0.12 + 0.18 + 0.42}$$
$$= 0$$

For this problem, expert 1 and 2 combine rating for criterion, D,

$= 3 \times 0 + 4 \times 1 + 5 \times 0 = 4$

2.2 ELECTRE METHOD

The ELECTRE method development and origin can be traced to Roy and Vincke [14] and the acronym, ELECTRE, stand for, Elimination and Et Choice Translating Reality. The basic concept of the multi criteria technique is based on paired comparisons of alternatives with reference to some certain decision criteria. The technique has been used by different researchers in solving multi-criteria decision problems in different domain. Shanian, Milani, Carson and Abeyaratne [15] utilise the technique in solving a material selection problem and Sevkli [16] integrated ELECTRE with a fuzzy logic technique in addressing a supplier selection problem. The method is applied in this paper, to address the challenge of risk prioritisation of ship system. The steps involved in the ELECTRE method are as follows [17]:

Step 1: Decision matrix formation: ELECTRE method process begins with the construction of a decision matrix with alternatives, j with respect to criteria, i. Since the Dempster Shafer theory is integrated with the method, the evaluated data from the Dempster Shafer combination rule is used to form the decision matrix. An example of such a decision matrix with element xij is presented in Table 1.

Table 1 : Inspection interval alternatives decision table

Failure modes (Aj)	Decision criteria (Bi)		
	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: Normalisation of the decision matrix: The normalisation of the decision matrix xij is performed as follows:

$$p_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}}}, i = 1,2 \ldots, n; j = 1, \ldots, m \quad (2)$$

Where pij is the normalised decision matrix

Step 3: Weighted normalised matrix formation:
The weighted normalised matrix v_{ij} is obtained by multiplying decision criteria weights, w_j, with the normalised decision matrix and is presented as follows:

$$v_{ij} = w_j p_{ij}, \quad i = 1, \ldots, n; \quad j = 1, \ldots, m \quad (3)$$

Step 4: Concordance interval matrix formation: Given a pair of failure modes, (alternatives) A_j and A_k, the concordance index $c_1(j_1, k)$ can be estimated as the sum of all weights for those decision criteria where the weighted normalised score of A_j is greater than or equal to A_k, as follows:

$$c_1(j, k) = \sum_{v_i(j) \geq v_i(k)} w_i, \quad j, k = 1, \ldots,; \; j \neq k \quad (4)$$

Where $v_i(j)$ and $v_i(k)$ are the weighted normalised scores of the j_{th} and k_{th} alternatives respectively. The concordance evaluation results are then used to form the concordance matrix as follows:

$$C_I = \begin{bmatrix} - & c_I(1,2) & \cdots & c_I(1,m) \\ c_I(2,1) & - & \cdots & c_I(2,m) \\ \vdots & \vdots & \ddots & \vdots \\ c_I(m,1) & c_I(m,2) & \cdots & - \end{bmatrix} \tag{5}$$

Step 4: Discordance interval matrix formation: The discordance index $d_1(j, k)$, is evaluated as:

$$d_I(j,k) = \begin{cases} 0, & \text{if} \quad v_i(j) \geq v_i(k) \quad i = 1,2,\ldots,n \\ \dfrac{\max\limits_{v_i(k)>v_i(j)} [v_i(k) - v_i(j)]}{\max\limits_{i=1\ldots n} [|v_i(k) - v_i(j)|]}, & \text{otherwise} \qquad j,k = 1,2,\ldots,m.\ j \neq k \end{cases} \tag{6}$$

The information obtained from the discordance index is then used to form the discordance matrix presented as follows:

$$D_I = \begin{bmatrix} - & d_I(1,2) & \cdots & d_I(1,m) \\ d_I(2,1) & - & \cdots & d_I(2,m) \\ \vdots & \vdots & \ddots & \vdots \\ d_I(m,1) & d_I(m,2) & \cdots & - \end{bmatrix} \tag{7}$$

Step 5: Determination of the performance index:
Two indices, net superior values, C_a, and net inferior values, D_a use for measuring performance of failure modes (alternatives) are evaluated respectively as follows:

$$C_a = \sum_{k=1}^{m} c_I(j,k) - \sum_{j=1}^{m} c_I(k,j) \quad j \neq k \tag{8}$$

$$D_a = \sum_{k=1}^{m} d_I(j,k) - \sum_{j=1}^{m} d_I(k,j) \quad j \neq k \tag{9}$$

The two performance indices for prioritising failure modes will yield two rankings. The two rankings can either be applied individually or both can be averaged to generate overall ranking.

3.0 CASE STUDY

In this section, the marine diesel engine is considered to demonstrate the suitability of the integrated Dempster Shafer theory and ELECTRE method. The marine diesel engine was chosen because it is one of the key ship machinery systems as it provides the power for the propulsion of the entire ship system. In addition, the marine main engine accounts for over 45 percent of the total compensation for fault accident claims of the entire ship system according to the survey carried out by a Swiss shipping insurance Company [18]. It is then obvious that the marine diesel engine is central to the operation, of not only the machinery systems, but of the entire ship system powered by this type of engine. A total of 23 failure modes were identified in bits from combinations of different sources such as literatures, data logged records and experts' opinions. Causes of failure, together with effects for each of the failure mode are presented in Table 2.

Table 2: FMEA for marine diesel engine [2, 5, 20-24]

S/N	Failure modes	Failure cause	Local effects	Global effects
1	Hole in the piston crown	Dripping of fuel valve	Escape of combustion gas into the crankcase	Reduced engine performance, engine damage and stoppage
2	Piston ring scuffing	Lack of lubrication, liner roundness fault	Oil smoke from exhaust, blow-by	Reduced engine performance
3	Piston ring cracked	Excessive gap pressure, worn-out ring groove	Oil smoke from exhaust, loss of power	Reduced engine performance
4	Piston ring /groove side face wear	Liquid fuel degrading lubricant in ring grooves	Loss of power	Reduced engine performance, engine stop
5	Piston ring stuck in grooves	Insufficient clearance during installation, deposits	Excessive clearance, fire blow	Reduce engine output, Stop engine
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23	Crankcase relief valve inoperable	Not seated properly	Allow air escape into crankcase	Reduce engine performance, explosion probable

In this paper, it is assumed that the FMEA team consists of two experts with equal expertise. Each of the expert ranks each of the 23 failure modes based on 3 decision criteria; O, S and D on an ordinal scale of 1-10. Table 3 represents the failure modes rating by two experts of which some are precise and others are imprecise rating. Because the proposed methodology utilised decision criteria weights in the decision making process, these weights were evaluated using the Analytical Hierarchy Process (AHP) see[19] for description of the AHP. The weights obtained for O, S and D, using AHP are 0.4, 0.4 and 0.2 respectively.

Table 3: Expert 1 and 2 imprecise decision criteria rating

Failure modes	Risk criteria rating						
	Expert 1				Expert 2		
	O	S	D		O	S	D
1	7:30%	3	4:70%		7:30%	4	4:40%
	8:70%		3:30%		8:70%		5:60%
2	7	6:50%	8		6	6	7
		5:50%					
3	5	6	5: 100%		5	8	6
4	7	3	3: 80%		7:70%	4	4
			2: 20%		6:30%		
5	7: 100%	6	5: 50%		6	7	5:80%
			4:50%				6:20%
…	…	…	…		…	…	…
23	7:80%	2	9:90%		7:60%	3	9
	6:20%		8:10%		5:40%		

The Dempster Shafer combination technique was applied to the imprecise ratings of decision criteria by expert 1 and 2 in Table 3 to obtain aggregated ratings. The aggregated ratings were used to form a decision matrix (refer to Table 4) which was then used as input data into the ELECTRE tool for the ranking of failure modes.

Table 4: Decision matrix

Failure mode	O	S	D
1	7.84	3.5	4
2	6.5	5.89	5.5
3	5	7	5.5
4	6.95	3.5	3
5	6.5	6.5	5
…	…	…	…
23	7	2.5	8.99

In applying the ELECTRE method to rank risk of failure modes, the decision matrix in Table 4 was normalised using Eq. 2. Then, weighted normalised decision matrix was obtained which is a product of the normalised decision matrix and the weights of the decision criteria. The formation of the concordance interval matrix and the discordance interval matrix using Eq. 4 and 6 respectively was then performed. Based on the concordance matrix and the discordance matrix, the net superior, Ca, and net inferior, Da, values of the different failure modes were calculated using Eq. 8 and 9 and the results are presented in Table 5. Finally, the different failure modes were ranked using their net superior and inferior values and the rankings generated are also presented in Table 5. The performance of the different failure modes could be determined by applying either the net superior index or net inferior index or an average of both. For the net superior index, the greater the value the higher the risk possess by the failure mode. In applying the net inferior value index in determining performance of the different failure modes, the lower the net inferior value the higher the risk the failure mode possess to the system.

From Table 5, the two ranking indices produce quite dissimilar rankings for all the 23 failure modes. The net superior index ranked failure mode 10 in the first position and as such was the most critical failure mode of the marine diesel engine. The net inferior index ranked the same failure mode in the second position.

Table 5: ELECTRE II ranking of failure modes

Failure modes	Ca	Rank	Da	Rank
1	-0.4000	14	0.9508	14
2	1.6000	9	-9.4283	5
3	2.4000	7	-7.8602	7
4	-8.6000	23	12.9899	20
5	4.2000	6	-13.3375	3
6	0.2000	13	-5.1153	10
7	-6.6000	19	17.5393	23
8	7.2000	3	-17.5729	1
9	2.4000	7	-11.5548	4
10	11.2000	1	-16.3682	2
11	-3.0000	16	12.7088	19
12	-7.2000	21	14.2723	21
13	-1.4000	15	9.1666	16

14	1.2000	10	-3.8566	12
15	5.6000	5	-5.8254	8
16	0.6000	11	4.0543	15
17	0.2000	12	0.6266	13
18	8.4000	2	-5.3497	9
19	-5.2000	18	10.3197	17
20	6.4000	4	-9.0052	6
21	-6.8000	20	12.4422	18
22	-8.4000	22	14.3962	22
23	-4.0000	17	-4.1927	11

For the net superior index failure mode 4 ranked in the last position, indicating the least critical failure mode of the marine diesel engine while failure mode 7 ranked in the last position by the inferior index. The net superior index is commonly used as the optimum ranking technique. However some researchers have combined the two performance indices to obtain overall ranking of alternatives. The net superior index is recommended for risk prioritisation of ship system because it generates the same results as the PROMETHEE technique applied by Maheswaran and Loganathan [9]. This is illustrated in section 3.1.2.

From Table 5, the two ranking indices produce quite dissimilar rankings for all the 23 failure modes. The net superior index ranked failure mode 10 in the first position and as such was the most critical failure mode of the marine diesel engine. The net inferior index ranked the same failure mode in the second position. For the net superior index failure mode 4 ranked in the last position, indicating the least critical failure mode of the marine diesel engine while failure mode 7 ranked in the last position by the inferior index. The net superior index is commonly used as the optimum ranking technique. However some researchers have combined the two performance indices to obtain overall ranking of alternatives. The net superior index is recommended for risk prioritisation of ship system because it generates the same results as the PROMETHEE technique applied by Maheswaran and Loganathan [9]. This is illustrated in section 3.1.2.

3.1 Comparison of ELECTRE method with other methods

3.1.1 Comparison of the ELECTRE method with the conventional FMEA

As stated in the introduction section, one of the challenges of the conventional FMEA, is its inability to utilise imprecise information from experts. To overcome this challenge and for unbiased comparison with the proposed technique, the aggregated data shown in Table 4 was also used as an input into the conventional FMEA. The ranking of risk of failure modes produced by the two methods are shown in Figure 1.

From Figure 1, it is obvious that the rankings produced by the conventional FMEA differ considerably from that of the ELECTRE method as the majority of the failure modes are ranked differently. The variation is as a result of the limitations of the conventional FMEA which are as follows:

- The inability of the FMEA to consider decision criteria weights in the decision making process whereas in the ELECTRE methodology, the decision criteria weights are put into consideration.
- The multiplication of O, S and D in evaluating RPN of the conventional FMEA is not rational.

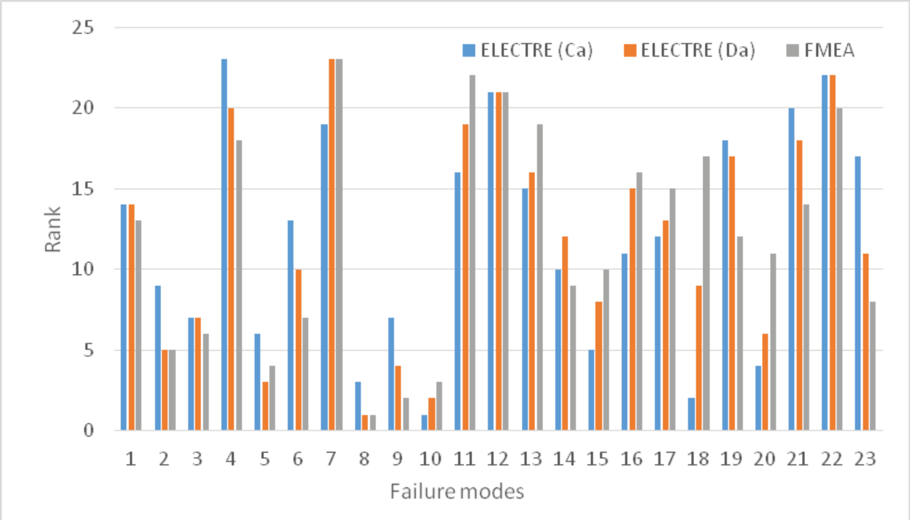

Figure 1: Comparison with conventional FMEA

These are some of the reasons why alternative approaches such as MCDM based methodology is recommended in the literature [7, 9]. The proposed methodology discussed in this paper overcomes all of these limitations of the conventional FMEA.

3.1.2 Comparison of the ELECTRE method with PROMETHEE method

In order to validate the novel technique, it was compared with the PROMETHEE method applied by Maheswaran and Loganathan [9]. Maheswaran and Loganathan [9]do not consider imprecise information from experts but use crisp values in the decision making process. However, in order to allow the use of both precise and imprecise information from experts, the data in Table 5 evaluated with the Dempster Shafer theory's combination technique was used as an input in the PROMETHEE methodology. The results of a comparative analysis of both the ELECTREE and the PROMETHEE technique are presented in Figure 2.

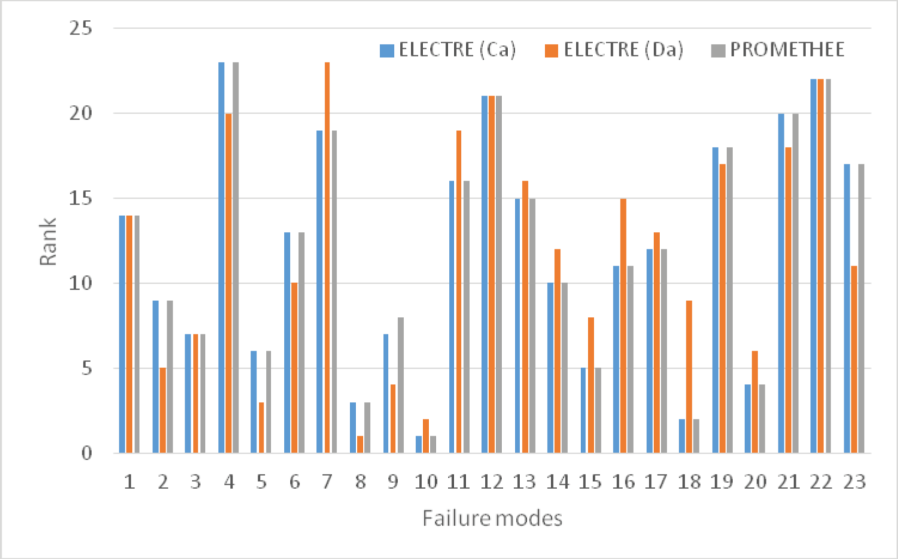

Figure 2: Comparison with PROMETHEE method

From Figure 2, the ELECTRE method (net superior (Ca)) and the PROMETHEE produces the same rankings for the 23 failure modes. However the ELECTRE method (net inferior (Da)) produces different ranking for most of the failure modes. On this basis, the ELECTRE method (net superior (Ca)) is recommended for prioritising risk of failure modes of ship systems. Although, Ca, produces the same results with that of the PROMETHEE technique applied by Maheswaran and Loganathan [9], it is easy to apply irrespective of the number of decision criteria utilised in prioritising risk of failure mode as opposed to PROMETHEE whose evaluation process complexity increases as the number of decision criteria increases. Furthermore, the ELECTRE method does not require the maintenance practitioners to determine the preference function for each of the decision criteria which is one of the drawbacks of the PROMETHEE technique. The PROMETHEE technique as applied by Maheswaran and Loganathan [9] for risk of failure mode prioritisation only considers precise information from experts and in most real life situation, information may be precise and imprecise. The integration of the Dempster Shafer combination technique with the ELECTRE method and PROMETHEE method make it possible for both techniques to utilise both precise and imprecise data from experts.

4.0 CONCLUSION

The purpose of this paper was to develop a systematic approach for risk prioritisation which avoids the limitations of the traditional FMEA and its variant in order for risk to be prioritised more effectively. To achieve this objective a novel FMEA tool which combines the Dempster Shafer Theory with the ELECTRE method is presented. The Dempster Shafer Theory is used to aggregate imprecise failures modes rating from experts while the ELECTRE method is used in the ranking of failure modes. In demonstrating the applicability and validity of the proposed method, a case study of marine diesel engine is applied. The results of the case study analysis reveal the following:

- The proposed method distinguishes failure mode from each other than the traditional FMEA approach whilst avoiding the limitations of the traditional FMEA such as inability to utilise imprecise information from experts.
- The proposed method produces almost completely the same results as that of the PROMETHEE technique used by Maheswaran and Loganathan [9] thereby validating the proposed approach.
- The proposed technique is easy to apply irrespective of number of decision criteria used in prioritising risk of failure mode unlike the PROMETHEE technique whose analysis difficulty increases as the number of decision criteria increases.
- The proposed technique does not require maintenance practitioners to define preference function for each decision criteria which is an additional burden created by PROMETHEE approach.

In conclusion, it is evident from this research that the proposed method is capable of solving risk prioritisation problem more effectively than the traditional FMEA approach and its variants. Further work can be performed by incorporating other decision criteria such as environmental impact and expected revenue into the risk prioritisation process.

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