APPLICATION OF WASPAS IN EHANCING RELIABILITY CENTERED MAINTENANCE FOR SHIP SYSTEM MAINTENANCE

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ABSTRACT

The key for achieving safe and reliable ship system operation throughout a vessel's life cycle is the continuous use of an effective maintenance methodology for the machinery systems. A typical maintenance methodology consists of three major elements which include; risk assessment, maintenance strategy selection and maintenance scheduling. The degree of ship system safety and reliability greatly depend on the successful execution of these elements. One approach for the implementation of these elements is Reliability Centred Maintenance (RCM). However, the various tools used within the RCM approach all have one limitation or another which reduces the effectiveness of the method. This paper presents the Weighted Aggregated Product Assessment (WASPAS), a Multi-Criteria Decision Making (MCDM) tool used to enhance the RCM method in order to improve its effectiveness in marine maintenance system applications. Although the typical maintenance methodology consists of three components, this paper focuses only on two of these, namely; risk assessment and maintenance strategy selection. With respect to risk assessment, WASPAS has been combined with Failure Mode and Effects Analysis (FMEA) along with Standard Deviation (SD). The maintenance strategy selection task has also been executed using a combination of WASPAS and SD. For both components, WASPAS is applied in the ranking of alternatives whilst SD has been used in the weighting of decision criteria. To illustrate the effectiveness of the proposed enhanced RCM methodology, a case study of the central cooling system of a marine diesel engine is presented.

KEYWORDS: RCM; ship system; WASPAS; SD; decision criteria

1.0 INTRODUCTION

The contribution of the shipping industry to the economic growth of the world cannot be over emphasized as the industry is responsible for the transportation of the bulk of the world's economic raw materials and merchandise. The business environment is highly competitive, despite the large market that it serves and this is due to the fact that there are so many service providers in the industry competing for the market. The key for any service provider to remain in business is the provision of reliable and quality services to its customers at a minimum cost. Unfortunately, the cost of ship operation keeps increasing and one of the major factors responsible for this is the high cost of ship maintenance which generally varies from 15 to 70 % of the total operational cost (Sarkar et al., 2011, Bevilacqua and Braglia, 2000). Alhouli et al. (2010) estimated that maintenance cost accounts for about 40 percent of the total operational cost of a ship; this

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assertion was based on their findings from the maintenance cost analysis of a 75,000 tonne bulk carrier.

It is obvious, that reducing the cost of maintenance will result in a significant reduction in the overall cost of ship operation. However, adequate care must be taken in reducing maintenance cost in order not to compromise reliability and safety of equipment, personnel and the environment. To achieve this aim, two primary elements which form part of the maintenance system must be optimized. These elements are; Risk assessment and maintenance strategy selection.

Risk assessment is central to the maintenance of a ship and its systems because the degree of risk of each equipment item that makes up the full integrated system will determine the maintenance strategy suitable for each item. There are basically three types of maintenance strategy; Corrective Maintenance (CM), Preventive Maintenance (PM) and Condition-Based Maintenance (CBM). PM is of two types; Scheduled Replacement (SR) and Scheduled Overhaul (SO). CBM is also of two types; continuous and periodic condition monitoring (Mishra and Pathak, 2012).

One popular approach for carrying out risk assessment and maintenance strategy selection is Reliability Centred Maintenance (RCM). The approach has been used in the marine industry to perform these tasks (Conachey, 2005;Conachey and Montgomery, 2003). However, tools used in RCM for performing these tasks all have one limitation or another. For example, Risk Priority Number (RPN) used for evaluating risk of failure modes within the Failure Mode and Effects Analysis (FMEA) framework is limited to the use of only three decision criteria, thereby excluding other important factors such as economic cost and environmental impact (Zammori and Gabbrielli, 2012; Liu et al., 2011).

Another example, is the RCM logic tree used for selection of the maintenance strategy which has been criticized as being a very time consuming exercise (Waeyenbergh and Pintelon, 2004). The technique also lacks the ability to rank maintenance strategy alternatives, thereby making the decision process difficult. Although alternative approaches have been reported in the literature, the developed techniques also have one challenge or another. For example, Lazakis et al. (2012) applied an integrated fuzzy logic set theory and TOPSIS. The practical application of the fuzzy logic technique however is still doubt because of the computational complexity it brings into the decision making process (Zammori and Gabbrielli, 2012). Goossens and Basten (2015) used AHP in a solving maintenance strategy selection problem for naval ship systems. However, formation and analysis of numerous pairwise judgments from experts make the decision process difficult.

From the above review it is established that there is a need to develop alternative tools that will enhance the decision making process within the RCM framework. In this paper, integrated WASPAS and SD methods are proposed for addressing the problems of risk assessment and maintenance strategy selection. The WASPAS method is applied in the ranking of alternatives whilst SD is used in evaluating decision criteria weights.

2.0 RISK ASSESSMENT

Risk is defined as the product of failure probability and the consequences of the failure. Within the framework of RCM, one popular tool applied for risk assessment is FMEA. FMEA is a systematic approach for identifying failure modes of a system, the causes and the corresponding effects of the failure. In evaluating risk of a failure mode of a system

within the FMEA framework, Risk Priority Number (RPN) is applied and it is generally expressed as the product of the occurrence of failure (O), the consequences of the failure (S) and the probability of detecting the potential failure (D) (Yang et al.,2011; Carpitella et al., 2017). Equation (1) shows values assigned to the three decision criteria; O, S and D by experts, based on a predetermined scale, as presented in Table 1.

$$RPN = O \times S \times D \tag{1}$$

Table 1. Scale for rating of O, S and D (Emovon et al., 2015; Cicek and Celik, 2013; Pillay and Wang, 2003; Yang et al., 2011)

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

However, despite the popularity of FMEA, the approach has limitations such as (1) the application of only three decision criteria in prioritizing risk of failure modes thereby excluding other important criteria such economic factors (Zammori and Gabbrielli, 2012) and (2) the assumption that decision criteria have equal weights where, in the real world, such an assumption may not be true (Carmignani, 2009; Chang and Sun, 2009). Hence,

in this paper an approach which avoids such limitations is proposed. To enhance the FMEA methodology, an integrated WASPAS and SD system is developed.

3.0   MAINTENANCE STRATEGY SELECTION

In the maintenance of ship systems, the same strategy may not be economically viable to maintain all of the equipment items of the system. A mix of different maintenance strategies is generally required in order for the systems to remain safe and reliable at minimum cost. There are basically three types of maintenance strategy; corrective maintenance (CM), Preventive maintenance (PM) and Condition Based Maintenance (CBM). However, PM can further be divided into two options; Scheduled overhaul (SO) and Scheduled replacement (SR) (Rausand and Vatn, 1998) while CBM also can be divided into two types; scheduled on-condition (SCBM) and continuous condition (CCBM) (Rausand and Vatn, 1998; Mishra and Pathak, 2012; Emovon, 2016a). CM is a maintenance approach in which equipment items are allowed to fail before being fixed. In the SO type of PM, equipment overhaul or repair is performed at regular time intervals while in the SR type, equipment items are replaced at specified time intervals. In the SCBM type of CBM, condition of an equipment item is monitored periodically while in the CCBM type, the condition of an equipment item is monitored continuously.

In this paper, CM, SO, SR, SCBM and CCBM are the five maintenance strategies identified for the maintenance management of ship systems. To select the optimal maintenance strategy for each equipment item, the technique conventionally used is the RCM logic tree. However, the method lacks the capacity to rank maintenance strategy alternatives. Furthermore, the exercise is time consuming (Waeyenbergh and Pintelon, 2004). Hence there is a need to develop an alternative approach that avoids such limitations. The use of MCDM tools becomes imperative. MCDM tools consider multiple decision criteria simultaneously in arriving at an optimal solution. In selecting the optimal maintenance strategy using the MCDM method, decisions are based on certain criteria and in this paper six types are utilized, as follows (Emovon, 2016a):

Spare parts inventories (C1): Each maintenance strategy requires different levels of spare parts availability.

Maintenance cost (C2): For each strategy, cost of equipment, materials and labour varies and the approach that is generally preferred is the one with the lowest maintenance cost.

Safety (C3): The maintenance strategy that will provide the highest level of safety for equipment, personnel and the environment is generally chosen.

Equipment reliability (C4): Each maintenance strategy produces a different degree of plant system reliability and the optimum strategy is generally the one that will produce the highest level of reliability.

Available monetary resource (C5): This criterion is central in determining the optimum maintenance strategy. Some Maintenance strategies are more capital-intensive especially at the initial stage of implementation than others. Companies with a low capital base may generally prefer CM or PM to CBM, irrespective of the benefits of the CBM.

Equipment risk level (C6): More attention is generally given to high risk equipment in terms of maintenance and budgetary allocation because their failure is usually

catastrophic and may cause irreversible damage to personnel, the environment and plant systems.

4.0   METHODOLOGY

4.1   Decision criteria weight determination: Standard Deviation (SD) Approach

Decision criteria weight determination is an important component of the overall decision making process because criteria weights greatly affect the ranking of alternatives. The SD technique is proposed in this paper because it is an objective weighting technique which will reduce human bias in the decision making process. The SD approach of decision criteria weights determination as the name implies utilises the SD of each criterion in ascertaining their relative importance, with the attribute having the greater SD being more significant than the ones with smaller SD (Wang and Luo 2010; Deng et al. 2000). The application of the SD method for criteria weight determination has been reported in the literature; Mohamed and Ahmed (2012) used the method to evaluate criteria weights in a project selection problem and Achebo and Odinikuku (2015) applied SD in determining decision criteria weights in a problem involving welding process parameter optimization. The SD method have been proven to produce similar criteria weights to that of Entropy method and Criteria Importance Through Inter-criteria Correlation (CRITIC) method (Wang and Luo 2010).

The SD methodological steps are as follows (Mohamed and Ahmed 2015):

Step 1. Decision matrix formation

Decision matrix formation is the first step in decision criteria weight determination. This is actually a model of the decision problem to be solved. The decision matrix is presented in Table 2.

Table 2. Decision matrix

Alternatives (Ai)	Decision criteria (Cj)					
	C1	**C2**	**C3**	**-**	**-**	**Cn**
A_1	x_{11}	x_{12}	x_{13}	-	-	x_{1n}
A_2	x_{21}	x_{22}	x_{23}	-	-	x_{2n}
A_3	x_{31}	x_{32}	x_{33}	-	-	x_{3n}
-	-	-	-	-	-	-
-	-	-	-	-	-	-
A_m	x_{m1}	x_{m2}	x_{m3}	-	-	x_{mn}

where A_i denotes the alternatives and i =1, 2, …m

C_j denotes the decision criteria and j = 1, 2,…n

x_{ij} is the rating assigned to alternative i with regard to the jth decision criterion.

Step 2. Normalisation of the decision matrix

The decision matrix is normalized as given in Equation (2) as follows:

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{2}$$

where r_{ij} is the normalized matrix.

Step 3: Determination of SD

The SD is evaluated individually for each decision criterion, as given in Equation (3) as follows:

$$sV_j = \sqrt{\frac{1}{m} \sum_{i=1}^{m} (r_{ij} - \bar{r}_j)^2} \tag{3}$$

where $\bar{r}_j$ denotes the mean value of the jth decision criterion and (sV_j) indicates SD for the jth decision criterion.

Step 4: Weight determination

The decision criteria weights, W_j are then evaluated as given in Equation (4) as follows:

$$W_j = \frac{sV_j}{\sum_{j=1}^{n} sV_j} \tag{4}$$

4.2 Ranking of alternatives: WASPAS Approach

WASPAS is a hybrid MCDM tool and was developed from a systematic combination of the Weighted Sum Model (WSM) and the Weighted Product Model (WPM). The methodology has been applied in solving decision problems involving multiple-criteria, for example Chakraborty and Zavadskas (2014) applied the technique to address eight different manufacturing decision problems.

The methodological steps of the WASPAS approach, as presented in the work of Yazdani et al (2016), are as follows:

Step 1: Normalization of the decision matrix

For the WASPAS method, the approach for decision matrix normalization depends on whether the decision criteria are beneficial or non-beneficial. For beneficial decision criteria normalization of the decision matrix in Table 1 is performed as expressed in Equation (5) as follows:

$$p_{ij} = \frac{x_{ij}}{\max_i x_{ij}}, \qquad j = 1,2,\ldots n, \qquad i = 1,2,\ldots m \tag{5}$$

For non-beneficial criteria, Equation (6) is used as follow: -

$$p_{ij} = \frac{x_{ij}}{\min_i x_{ij}}, \qquad j = 1,2,\ldots n, \qquad i = 1,2,\ldots m \tag{6}$$

Step 2: Performance index based on WSM and WPM

The performance index of the ith alternative using WSM is evaluated as given in Equation (7) as follows:

$$sQ_i = \sum_{j=1}^{n} p_{ij}.w_j \tag{7}$$

For WPM, the performance of the ith alternative is evaluated by applying the following expression:

$$pQ_i = \prod_{j=1}^{n} (p_{ij})^{w_j} \tag{8}$$

Equations (7) and (8) are aggregated systematically to form a single performance model for the ranking of alternatives as given in Equations (9) and (10) as follows:

$$Z = 0.5sQ_i + pQ_i = 0.5 \sum_{j=1}^{n} p_{ij}.w_j + 0.5 \prod_{j=1}^{n} (p_{ij})^{w_j} \tag{9}$$

$$Z = \lambda\, sQ_i + (1-\lambda)\, pQ_i = \lambda \sum_{j=1}^{n} p_{ij}.w_j + (1-\lambda) \prod_{j=1}^{n} (p_{ij})^{w_j} \tag{10}$$

The alternatives are ranked based on performance index, Z, and the optimal alternative is the one with the highest value of Z.

5.0   CASE STUDY

For this study the central cooling system had been chosen to demonstrate the applicability of the proposed methodology. The central cooling system consists of the fresh water cooling and sea water cooling sections. A typical example of the central cooling system is shown in Figure 1. The pumps of the sea water cooling system draw water from the sea via the sea chest. The sea water help cools the central coolers which circulate fresh water for the cooling of the marine diesel engine.

Figure 1. Central cooling system of a bulk carrier (DESMI et al, 2008, Emovon 2016a)

5.1   Risk Assessment Analysis

5.1.1 Data Collection

Having identified the system for investigation, the next step is to identify the failure modes of the system. Six failure modes were identified for six equipment items of the central cooling system. The six failure modes together with the failure causes and failure effects are presented in Table 3. For the six failure modes, three experts assigned ratings based on their experience and knowledge of the system. The three experts reached a consensus and the agreed rating of the failure modes is also presented in Table 3.

Table 3. Central cooling system failure modes and assigned ratings

FM #	Failure modes (FM)	Equipment items	S	O	D
1	Choked, leaks	Sea water Pipes	5	5	2
2	Operates at degraded head/flow performance	Sea water cooling pump	2	5	2
3	Leakage	Central cooler	2	5	3
4	Abnormal temperature	Lube oil cooler	5	8	4
5	Blocked	Thermostatic valve circuit	4	4	5
6	Unable to start	Engine preheating unit	6	4	4

5.1.2 Data analysis

To evaluate weightage of S, O and D, firstly the values in Table 3 were normalised using Eq. 2. This was followed by the determination of the standard deviation of each criterion using Eq. 3. Finally, the weights of S, O and D are evaluated whilst utilising Eq.4. The values of 0.3922, 0.2671 and 0.3406 were obtained for S, O and D respectively. Having determined criteria weights, the next stage is the ranking of the failure modes of the central cooling system. This stage begins with the normalization of the decision matrix using Equation 5 and the results produced are shown in Table 4. Next, is the determination of WSM and WPM by applying Equations 7 and 8 and the results generated are presented in Tables 5 and 6 respectively. Finally, using Equation 10 while assuming λ to be 0.5, the performance index, Z, of each of the failure modes is obtained and the results are shown in Table 7 and Figure 2. On the basis of the performance index, Z, failure modes are ranked and the results are also shown in Table 7 and Figure 2.

Table 4. Normalised decision matrix

FM #	S	O	D
1	0.8333	0.6250	0.4000
2	0.3333	0.6250	0.4000
3	0.3333	0.6250	0.6000
4	0.8333	1.0000	0.8000
5	0.6667	0.5000	1.0000
6	1.0000	0.5000	0.8000

Table 5. WSM analysis

FM #	S	O	D	sQi
1	0.3269	0.1670	0.1363	0.6301
2	0.1307	0.1670	0.1363	0.4340
3	0.1307	0.1670	0.2044	0.5021
4	0.3269	0.2671	0.2725	0.8665
5	0.2615	0.1336	0.3406	0.7357
6	0.3922	0.1336	0.2725	0.7983

Table 6. WPM analysis

FM #	S	O	D	pQi
1	0.6449	0.6199	0.5071	0.2028
2	0.4502	0.6199	0.5071	0.1415
3	0.4502	0.6199	0.5822	0.1625
4	0.6449	0.7028	0.6422	0.2911
5	0.5909	0.5841	0.6929	0.2391
6	0.6927	0.5841	0.6422	0.2598

Table 7. Performance index and ranking of FM

FM #	Z	RANK
1	0.4164	4
2	0.2877	6
3	0.3323	5
4	0.5788	1
5	0.4874	3
6	0.5291	2
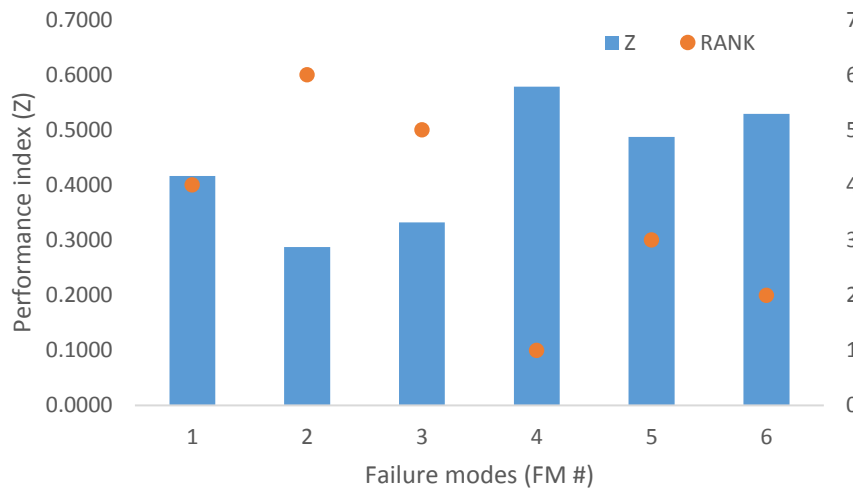
Figure 2**.** Performance index and corresponding rank of failure modes

From Table 7 and Figure 2, failure mode 4, having the highest performance index value of 0.5788, is ranked 1. This is followed by failure mode 6 with a performance index of 0.5291. The lowest ranked failure mode is failure mode 2 having the lowest performance index value.

Based on these results, failure mode 4 poses the highest risk to the central cooling system of the ship while failure mode 2 poses the least threat to the system. The greatest attention should be given to failure modes 4 and 6 in terms of maintenance and budgetary allocation in order to ensure safe and reliable ship system operation.

In order to validate the proposed approach, the WASPAS technique was compared with a well-known MCDM tool, TOPSIS (Emovon et al., 2015; Sachdeva et al., 2009) and the result of the comparative analysis is presented in Table 8 and Figure 3.

Table 8. Comparison of WASPAS and TOPSIS methods

FM #	WASPAS	TOPSIS
1	4	4
2	6	6
3	5	5
4	1	2
5	3	3
6	2	1
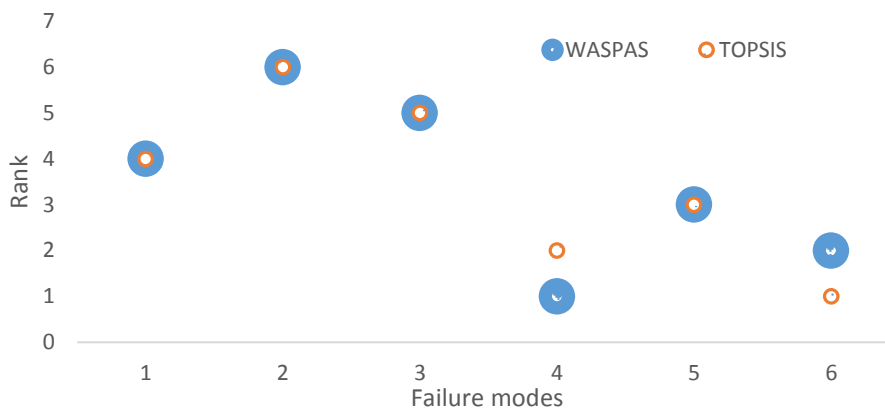
Figure 3. Comparison of WASPAS and TOPSIS methods

From Table 8 and Figure 3, failure modes 1, 2, 3 and 5 have the same rank for both the WASPAS and TOPSIS methods while failure modes 4 and 6 have a difference of one rank position. Given that the two highest ranked failure modes are the same, albeit with reversed rank, the comparison with TOPSIS validates the potential use of WASPAS in ranking failure modes.

5.2 Maintenance strategy selection Analysis

5.2.1 Data Collection

From the risk assessment analysis above, the sea water pump was identified as one of the equipment items which poses the highest risk to the operation of the central cooling system. On this basis, it was used to demonstrate the applicability of the proposed technique in the maintenance strategy selection problem. To achieve this objective, the data assigned by three experts to six different maintenance strategies with regard to certain decision criteria was adapted from the work of Emovon (2016a). The three expert-assigned ratings were averaged and the resulting decision matrix is shown in Table 9.

5.2.2 Data Analysis

The first step in the data analysis is the determination of decision criteria weights. Applying Equations 2-4 to the data in Table 9, the weights obtained are 0.1944, 0.0995, 0.1922, 0.1768, 0.1673 and 0.1698 for decision criteria C1, C2, C3, C4, C5 and C6 respectively. The next step is to rank the maintenance strategy alternatives using the WASPAS method. The WASPAS analysis starts with the normalization of the decision matrix using Equation 5. This is followed by the determination of WSM and WPM using Equations 7 and 8 and the results produced are presented in Tables 10 and 11 respectively. Finally, using Equation 10 and assuming λ to be 0.5, the performance index, Z, of each of the maintenance strategy alternatives is obtained and the results are shown in Table 12. On the basis of the performance index, Z, the failure modes are then ranked and the results are also shown in Table 12 and Figure 4.

Table 9. Decision matrix

Alternatives	Decision criteria					
	C1	C2	C3	C4	C5	C6
CM	1.3333	3.0000	1.0000	1.3333	4.0000	1.3333
SO	2.6667	3.0000	3.3333	3.3333	3.0000	3.3333
SR	2.0000	2.3333	3.0000	2.6667	1.6667	2.6667
SCBM	4.6667	4.3333	5.0000	5.0000	4.6667	5.0000
CCBM	4.3333	2.6667	5.0000	4.6667	2.0000	4.0000

Table 10. WSM Analysis

Alternatives	C1	C2	C3	C4	C5	C6	sQi
CM	0.0555	0.0689	0.0384	0.0472	0.1434	0.0453	0.3987
SO	0.1111	0.0689	0.1281	0.1179	0.1075	0.1132	0.6467
SR	0.0833	0.0536	0.1153	0.0943	0.0597	0.0906	0.4968
SCBM	0.1944	0.0995	0.1922	0.1768	0.1673	0.1698	1.0000
CCBM	0.1805	0.0612	0.1922	0.1651	0.0717	0.1359	0.8065

Table 11. WPM Analysis

Alternatives	C1	C2	C3	C4	C5	C6	pQi
CM	0.5701	0.7663	0.5346	0.5827	0.7226	0.5912	0.0581
SO	0.6524	0.7663	0.6738	0.6852	0.6887	0.6907	0.1098
SR	0.6169	0.7474	0.6602	0.6587	0.6242	0.6651	0.0832
SCBM	0.7273	0.7949	0.7284	0.7361	0.7415	0.7400	0.1701
CCBM	0.7169	0.7574	0.7284	0.7272	0.6435	0.7125	0.1319

Table 12. Performance index and ranking

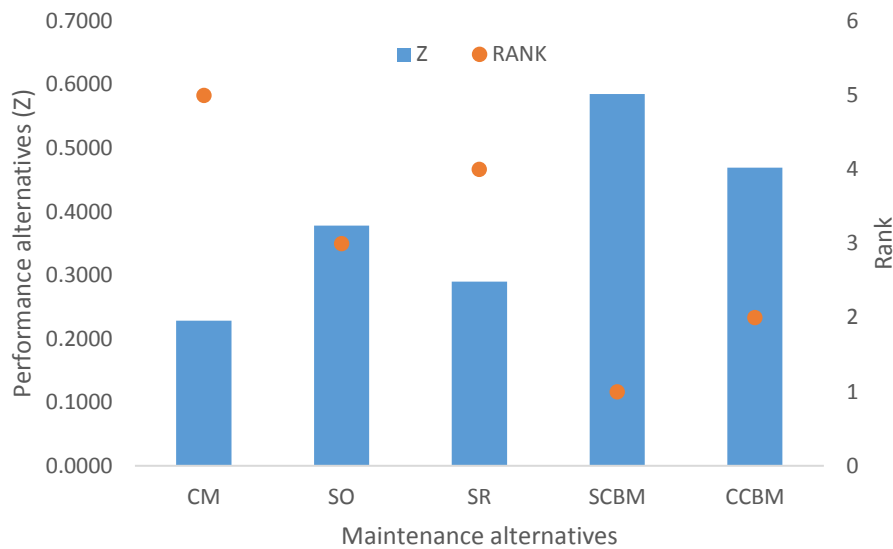| Alternative	Z	Rank
CM	0.2284	5
SO	0.3782	3
SR	0.2900	4
SCBM	0.5850	1
CCBM	0.4692	2

Figure 4. Maintenance strategy alternatives performance index and corresponding ranking

The results in Table 12 and Figure 4, indicate that, SCBM, is the optimal strategy for maintaining the sea water cooling pump, having rank position 1. The result also showed that the second choice solution is CCBM, having rank position 2. The worst maintenance strategy is CM, having rank position 5. The SCBM strategy identified as the optimal solution in this paper using the SD-WASPAS method, is in line with the current trend of maintenance of the system in the industry. To further, validate the WASPAS method for use as an appropriate technique for selecting maintenance strategies within the framework of RCM, the approach was compared with the TOPSIS method. The result of the comparative analysis showed that WASPAS and TOPSIS produced exactly the same results, thereby validating the WASPAS technique as a viable tool for ranking of maintenance strategy alternatives. The WASPAS approach is simple and yet has a strong resistance against rank reversal (Chakraborty, and Zavadskas, 2014). The technique is less computationally intensive when compared to TOPSIS, PROMETHEE and VIKOR methods (Urosevic, et al. 2017). These qualities will make the WASPAS method more attractive to analysts or decision makers in the maritime sector than TOPSIS and other, similar MCDM techniques.

6.0 CONCLUSIONS

In this paper, an integrated SD and WASPAS method is presented for prioritizing alternatives within the framework of RCM. The SD technique was applied in the evaluation of decision criteria weights whilst WASPAS was used in the ranking of the alternatives. The technique was developed to enhance RCM in order to mitigate the deficiencies of the standard FMEA and RCM logic tree methodologies used within the framework for prioritizing risk of failure modes and selecting an optimal maintenance strategy respectively. The research analysis indicated, that the proposed technique is a viable tool for ranking of alternatives as it produces almost completely the same result as another technique used in the literature, the TOPSIS method, in a case study of a failure mode risk prioritization problem and produces exactly the same result as the TOPSIS method in the case study of maintenance strategy selection whilst being less computationally intensive.

The RCM techniques are already routine for maintenance of an entire ship and as such the proposed enhanced RCM can easily be implemented for the whole ship because it will not require scaling up. The conventional RCM team will can implement the enhanced RCM method and once implemented, it would be straightforward for experts on board to apply it.

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