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Application of Analytic Hierarchy Process & TOPSIS methodology on ships' maintenance strategies

Keywords

ships' equipments maintenance strategies, ship safety, AHP & TOPSIS.

Abstract

The aim in adoption of maritime equipments' maintenance strategy is the reduction of risk in order to achieve safer navigation, to enhance environmental friendly behaviors, to increase the safety and positively contribute to the overall operability management of the ship. The use of weak maintenance strategy could result in waste of time, money and resources, and often has no effect on improving or maintaining the availability of equipments.

In this article, we propose a model in evaluation of on non-deterministic factors that affect the ships' safety and a framework for ships management governance. The review of maintenance strategies has proven that a decision support mechanism needs mainly multiple criteria decision on ship equipments maintenance strategy selection. Through Analytic Hierarchy Process methodology and the extended evaluation of results on adoption of Technique for Order Preference by Similarity to Ideal Solution a useful tool to prioritize needs at any level and includes the decisions that should be taken into consideration from the shore office managers and the ship personnel for the safe functionality of the ship is provided.

1. Introduction

The majority of technical and commercial activities within shipping industries cycle has been controlled continuously by the international authorities such as International Maritime Organization (IMO), International Transportation Federation (ITF), International Labor Organization (ILO), and other governmental and non-governmental organizations (NGOs) like flag states, port states, and chamber of shipping, etc. Furthermore, now days with increasing Technology development, the developing of industries automation and the increase of machinery quantity, the volume of investment in company's tangible assets and machineries has increased significantly. So the maintenance is an inevitable source of cost, and the increase in maintenance department can represent from 15 to 70% of total production costs [14] based on type of industry. So the increase of machinery quantity on ships machinery plan requires an optimal maintenance policy mix, in order to increase the plan availability and reduce the operating costs. This leads the shipping business operators, due to the inevitable cost of maintenance, to adopt maintenance strategies on equipments in order to comply with demands on reliability, to increase the safety at the lower possible cost.

A maintenance programme must be produced based on operational specific needs and objectives, taking into account the best practice. As an aid to the resolution of this problem, some multi-criteria decision making (MCDM) approaches are proposed in the literature. Almeida and Bohoris discuss the application of decision making theory to maintenance with particular attention to multi attribute utility theory [2]. Triantaphyllou et al. suggests the use of Analytical Hierarchy Process (AHP) [16] considering four maintenance criteria: cost, reparability, reliability and availability. The Reliability Centered Maintenance (RCM) methodology is a technique which provides a framework for utilizing operating experience in a more systematic way. RCM represents a method for preserving functional integrity and is designed to minimize maintenance costs by balancing the higher cost of corrective maintenance against the cost of preventive maintenance, taking into account [10]. The proposals from literature and many others are considered in design and construction phase for land based industries, aircraft industry and later they were adapted to several other industries [3], [17], [18], [9], but the examination of literature reveals that applications of analytical methods for maritime operations are rare.

In this paper the risk evaluation on equipments maintenance strategy (EMS) and the decision making of the best strategy is presented. The proposed approach is based on two-steps the AHP [11], [12] and then TOPSIS [8] methodology for selecting the most appropriate EMS. This leads to a more powerful tool than traditional methods and enhances the risk evaluation in complex ship systems.

2. Maintenance strategies

Generally, in service and manufacturing industries, maintenance is regarded as shop-floor activities, such as tightening nuts and bolts, lubricating bearings, or repairing machine parts when they break. Is this really what maintenance engineering is all about?

The British Standards Institution; BS3811:1974 gave a generally accepted approach on maintenance and defines it as: “A combination of any actions carried out to retain an item in or restore it to acceptable operational standard” [4]. From the definition; “actions” are those of initiation, organization, and implementation. Initiation activities may include the pre-purchase equipment appraisal, specification, installation, and commissioning of a facility. The “Acceptable conditions” will include factors such as Efficiency (fuel usage, power output, speed, etc.), Production of good quality product/ service and Safety of operations.

With these definitions, it can be clearly seen that maintenance involves more than “fixing a broken system”. It involves the use of technical as well as management expertise such as Engineering (design and construction), Management (scheduling, cost, information collection/analysis) and Accounting (profitability and investment in facilities).

It is clear that a good maintenance programme must define different strategies for different machines. Some of these will mainly affect the normal operation of the ship, some will concern relevant safety problems, and others will involve high maintenance costs. The overlapping of these effects enables us to assign a different priority for every ship machinery system or component, and to concentrate the economics and technical efforts on areas that can produce the best results.

The definitions of the maintenance strategies are based on reliability data from the literature and on the technical feature of the machines. This information then is updated using the data acquired from experts during the working life of the ship equipments. The analysis system has been structured in a rational way so as to keep the update process as objective as possible. Furthermore, to evaluate the best equipments maintenance strategy, due to the large number of equipments that consist the ship operational system (pumps, compressors, coolers, etc.), the ship equipments system is divided into groups with different characteristics. Then, these groups will correspond to different maintenance strategies [7], [17]. The main characteristics of these groups are the following:

- Machinery group 1. A failure in this group can lead to serious consequences in terms of workers safety, in a system of the ship and environmental damages, etc. Significant savings can be obtained by reducing the failure frequency and the downtime length. A careful maintenance (i.e. Fixed Time Maintenance or predictive) can lead to good levels of ship's company added-value. In this case, savings in maintenance investments are not advisable. This group contains the critical equipment and the bigger percentage of the ship machines.
- Machinery group 2. The damages derived from a failure can be serious but, in general, they do not affect the external environment. A medium cost reduction can be obtained with an effective but expensive maintenance. Then an appropriate cost/benefit analysis must be conducted to limit the maintenance investments. For this reason Condition Based maintenance is preferable to a more expensive predictive policy.
- Machinery group 3. The failures do not affect the ship system. The spare parts are not expensive and, as a consequence, low levels of savings can be obtained through a reduction of spare stocks and failure frequencies. With a tight budget the maintenance investments for these types of facilities should be reduced, also because the added-value derived from a maintenance plan is negligible. The cheapest Run to Failure or corrective maintenance is, therefore, the best choice. This group contains the lowest percentage of the machines.

The three alternative maintenance strategies which are evaluated in this study briefly are the following:

- Predictive Maintenance or Fixed/ Scheduled Time Maintenance (FTM). This is a Time Interval based maintenance practice; practices in this category include shut down maintenance which is pre–planned. It’s an action that can be performed on any critical or non critical equipment and is based on equipment reliability characteristics. This data makes it possible to analyze the behavior of the element in question and allows the maintenance engineer to define a periodic maintenance program for the machine. The FTM strategy tries to determine a series of checks, replacements and/or component revisions with a frequency related to the failure rate. In other words, FTM is effective in overcoming the problems associated with the wearing of components.

- Preventive or Condition Based maintenance. A requisite for the application of condition-based maintenance is the availability of a set of measurements and data acquisition systems to monitor the machine performance in real time. The continuous survey of working conditions can easily and clearly point out an abnormal situation (e.g. the exceeding of a controlled parameter threshold level), allowing the process administrator to punctually perform the necessary controls and, if necessary, stop the machine before a failure can occur.
- Corrective or Run-to- Failure Maintenance. The main feature of Run-to- Failure maintenance is that actions are only performed when a machine breaks down at an unexpected time. There are no interventions until a failure has occurred. Also a Run-to-Failure maintenance strategy is proposed especially in cases where the cost of maintenance is more than the cost of replacing equipment or part of it after failure. The Run to Failure Maintenance strategy is applied to equipments that are not related with ships safety or its availability.

3. The Analytic Hierarchy Process

The AHP was developed in 1980 by Thomas Saaty. It’s a powerful and flexible multi-criteria decision making tool and allows decision makers to model complex problems where both qualitative and quantitative aspects need to be considered [12], [13]. The AHP helps the decision makers to organise the critical aspects of a problem into a hierarchical structure that involves structuring multiple choice criteria into a hierarchy, assessing the relative importance of these criteria, comparing alternatives for each criterion and determining an overall ranking of the alternatives [6], [5].

Step-by-step procedure in using AHP is the following: First define decision criteria in the form of a hierarchy of objectives. The hierarchy is structured on different levels from the top (the goal) through intermediate levels (criteria and sub-criteria on which subsequent levels depend) to the lowest level (the alternatives). Then the criteria, sub-criteria and alternatives are evaluated according to their influence and their importance for the corresponding element of the higher level. For this purpose, AHP uses simple pairwise comparisons to determine weights and ratings so that the analyst can concentrate on just two factors at one time. One of the questions which might arise when using a pairwise comparison is: how important is the “maintenance strategy cost” factor with respect to the “maintenance strategy applicability” attribute, in terms of the “maintenance policy selection” (i.e. the problem or goal)? The answer may be “equally important”, “weakly more important”, etc. The verbal responses are then quantified and translated into a score via the use of discrete 9-point scales *Table 1*.

Table 1. Scale used for pairwise comparisons

Intensity of importance	Value description	Explanation
1	Equal importance.	i and j are equally important
3	weak importance	i is slightly more important than j
5	strong importance	i is strongly more important than j
7	Very strong importance.	i is very strongly more important than j
9	extreme importance	i is absolutely more important than j
2,4,6,8	Intermediate values	When a compromise in judgment is needed.

After a judgment matrix has been developed, a priority vector to weigh the elements of the matrix is calculated. Then calculate Consistency Index *(CI)* and consistency ratio *(CR)* to check the consistency of Criteria and Alternatives with respect to the Goal and finally calculate the final priorities. This is a straightforward matter of multiplying and adding, carried out over the whole of the hierarchy and the results give to us the overall priorities and the solution for making the decision. In the proposed model, a typical AHP hierarchy for best equipments maintenance strategy through the expert’s judgments is shown in *Figure 1*.

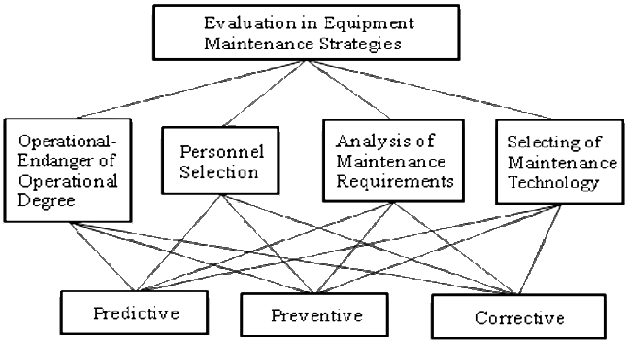

Figure 1. Hierarchical structure of the evaluation in Equipment Maintenance Strategies problem.

4. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The TOPSIS method introduced by Hwang and Yoon in 1981 with further developments by Yoon in 1987 [8] and based on the idea that the best alternative should have the shortest distance from the positive ideal solution and farthest distance from the negative ideal solution. TOPSIS is a multiple criteria decision making (MCDM) method to identify solutions from a finite set of alternatives. The TOPSIS method evaluates the decision matrix $X = \lfloor x_{ij} \rfloor_{mxn}$ which refers to *m* alternatives which are evaluated in terms of *n* criteria and denotes the performance measure of the *i*th alternative in terms of the *j*th criterion. Its steps are as follows :

Step 1. Calculate the normalized decision matrix $R = [r_{ij}]_{mxn}$ where *m* is the number of alternatives and *n* is the number of criteria. The normalized value r_{ij} is calculated as:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \qquad i = 1,2,....,m; j = 1,2,...,n \qquad (1)$$

The normalization is done for convenience of comparison by converting different units of criteria to a unified unit.

Step 2. Calculate the weighted normalized decision matrix $V = \lfloor v_{ij} \rfloor_{mxn}$. The weighted normalized value is calculated as:

$$v_{ij} = (w_j)(r_{ij}) \qquad i = 1,2,....,m; j = 1,2,...,n \qquad (2)$$

where w_{ij} is the weight of the *j*th criterion and $\sum_{i=1}^{n} w_j = 1$.

Step 3. Determine the positive ideal solution (PIS) A^+ and negative ideal solution (NIS) A^- :

$$A^+ = \left\{\left(\max_i v_{ij} \middle| j \in J\right), \left(\min v_{ij} \middle| j \in J'\right) \middle| i = 1,2,...,m\right\} = \left\{v_1^+, v_2^+, ..., v_j^+, ..., v_n^+\right\} \qquad (3)$$

$$A^- = \left\{\left(\min_i v_{ij} \middle| j \in J\right), \left(\max v_{ij} \middle| j \in J'\right) \middle| i = 1,2,...,m\right\} = \left\{v_1^-, v_2^-, ..., v_j^-, ..., v_n^-\right\} \qquad (4)$$

Where

$J = \{j = 1,2,...,n | j$ *associated with the criteria having a positive impact*$\}$

$J' = \{j = 1,2,...,n | j$ *associated with the criteria having a negative impact*$\}$

Step 4. Calculate the separation measures, using the n-dimensional Euclidean distance.

The separation of each alternative from the positive ideal solution:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2} \qquad i = 1,2,....,m \qquad (5)$$

The separation of each alternative from the negative ideal solution:

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2} \qquad i = 1,2,....,m \qquad (6)$$

Step 5. Calculate the relative closeness to the ideal solution:

$$c_i = \frac{S_i^-}{\left(S_i^+ + S_i^-\right)}, 0 \prec c \prec 1, \quad i = 1,2,....,m \qquad (7)$$

$$c_i = 1 \quad if \quad A_i = A^+$$

$$c_i = 0 \quad if \quad A_i = A^-$$

Step 6. Rank the alternatives with respect to c_i in the descending order. The preferred alternative should have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution, where a higher c_i would mean higher preference.

5. Application integrated AHP and TOPSIS approach for Equipment Maintenance Strategies evaluation.

The AHP hierarchy is developed in this study in three levels. The first level represents the main goal of maintenance selection and the lowest level comprises the alternative maintenance strategies. The evaluation criteria that influence the primary goal are included at the second level and are related to four different risk aspects: Operational- Endanger at the Operational Degree, Personnel Selecting, Analysis of the Maintenance Requirements, and Selecting Maintenance Technology *Figure 1*. The judgments of all the people concerned with maintenance problems in ship and onshore are included.

The relevant factors defining the Operational Endanger Degree criterion (OED)are identified as loss of propulsion power, loss of electric power, and failures of cargo handling facilities. These are related to the operational reliability of the ship, the damage to environment due to spilling or collision etc, the influence to personnel safety, and to the company's image.

The risk of Personnel Selecting factor (PS), concerns the importance of personnel selection. The optimal thought is on ship to have the best maintenance personnel for handling the maintenance. But the tendancy in shipping industry to decrease the number of personnel onboard could affect the safety when the crew must make all the repairs. Hence, this factor has different weight and influence for each one of the maintenance strategies at pairwise comparisons.

The criterion of Analysis of the Maintenance Requirements (AMR), takes into account the funds required for the strategy implementation, the availability of a spare part of equipment or the logistics chain requirements to be delivered on the ship.

Selecting Maintenance Technology (SMT) is another important criterion for a maintenance strategy implementation. The Selecting maintenance technology achieves improvement of maintenance results and provides predictability of failures that could lead to total failure of a machine.

A steering pump has been selected as a representative machine for the AHP analysis in this study. The hierarchy of equipment maintenance strategy criteria was determined through interviews with the experts-decision makers and accordingly the hierarchical structure of the problem was developed *Figure 1*. The decision had 3 alternatives to be evaluated under 4 main criteria. In first step AHP is used for calculating the weights of the attributes or criteria as well as the overall weights of the alternatives in each attribute. The composite weigh of criteria were determined using AHP and the inconsistency of each pairwise comparison matrix was examined by CR. When the level of inconsistency was found unacceptable, the elements of the related matrix were revised with the experts. In second step these weighs are considered and used in TOPSIS process. Then TOPSIS [15], [18], is applied for the evaluation problem and the result shows the preference order of the equipments maintenance strategy in ship machinery. This methodology levels is shown in *Figure 2*.

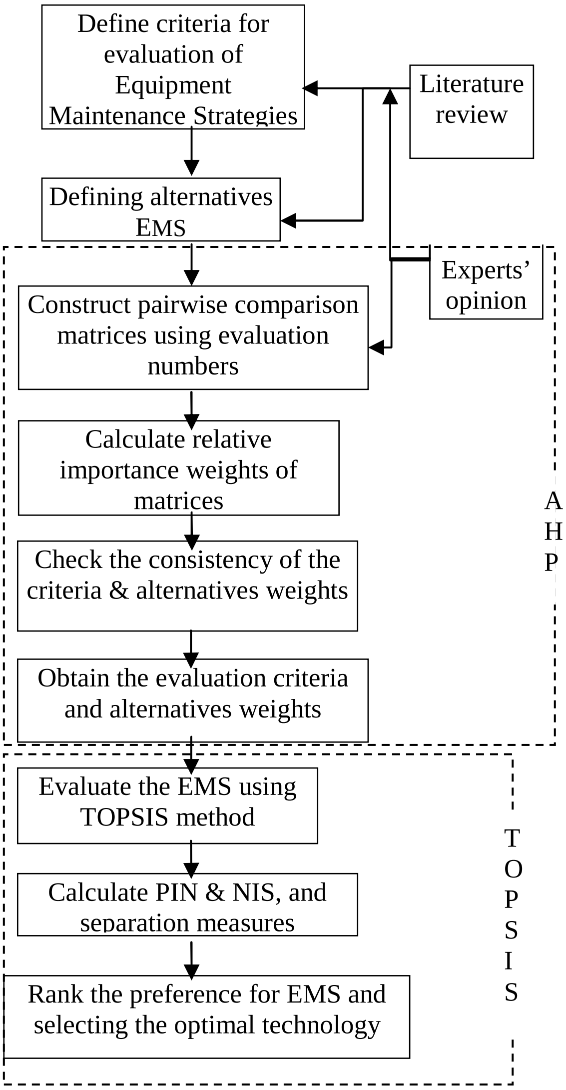

Figure 2. Schematic diagram of the proposed model for Equipments Maintenance Strategy selection

According the integration of AHP and TOPSIS methodology, indicative illustrated for ship steering gear the steps for criterion of Operational Endanger Degree as follows:

From experts judgments' according to Saaty's scale mentioned in Table 1 taking the pairwise comparison matrix for the criteria Operational Endanger Degree as shown in *Table 2*.

Table 2. Pairwise comparison matrix for Operational Endanger Degree OED

OED	Predictive	Preventive	Corrective	Pr. Vector
Predict	1	3	7	0,6491
Prevent	1/3	1	5	0,2790
Correct	1/7	1/5	1	0,0719
SUM	1,47	4,2	13	1

The priority vector is obtained from normalized Eigenvector of the matrix. Then compute the $\lambda_{\max}$ from the comparison matrix which from the *Table 2.* given $\lambda_{\max} = 3{,}0967$.

Then calculate Consistency Index (CI) and Consistency Ratio (CI). For Table 44 are:

$$CI = \frac{\lambda_{\max} - n}{n-1} = 0{,}04836 \tag{8}$$

and

$$CR = \frac{CI}{RI} = 0{,}0833 \tag{9}$$

This value of C.R is less than the allowable value of 0.10. Therefore, the consistency of the judgment matrix is found to be within an acceptable tolerance. The previous steps repeated for the other criteria and then calculate the weights for each alternative. The weights for each alternative against the other criteria and the goal values are shown in *Table 3.*

Table 3. Overall weight of the alternatives

MS	OED	PS	AMR	SMT	GOAL
Predict	0,3890	0,0184	0,0048	0,0320	0,4442
Prevent	0,1672	0,0429	0,0082	0,0724	0,2907
Correct	0,0431	0,1662	0,0497	0,0061	0,2651
Totals	0,5993	0,2275	0,0627	0,1105	1,0000

Then, the decision matrix for TOPSIS method was formed with the weights that carried out from AHP. By normalization of these data, construct the weighted decision matrix *Table 4* and from these determine the ideal and negative ideal solutions *Table 5*, calculate the separation measures for each alternative till finally calculate the relative closeness to the ideal solution as described in *paragraph 4*.

Table 4. TOPSIS normalized decision matrix

EMS	OED	P S	A M R	SM T
Predict	0,914006	0,106586	0,094861	0,403067
Prevent	0,392858	0,248507	0,162055	0,911939
Correct	0,101269	0,962748	0,982212	0,076835
Totals	0,59930	0,22750	0,06270	0,11050

Table 5. Separation measure from Positive and Negative Ideal Solution

EMS	OED	P S	A M R	SM T	S_i^+	S_i^-
Predict	0,54776	0,02425	0,00595	0,04454	0,206	0,490
Prevent	0,23544	0,05654	0,01016	0,10077	0,368	0,178
Correct	0,06069	0,21903	0,06158	0,00849	0,487	0,223

The results given by calculate the relative closeness to the ideal solution c_i equation (7) and the corresponding rank of the EMS.

$$c_i = \frac{S_i^-}{\left(S_i^+ + S_i^-\right)} \qquad 0 \prec c_i \prec 1$$

Table 6: Relative Closeness and Rank of Equipment Maintenance Strategies

EMS	c_i	Rank
Predictive	0,7044	1
Preventive	0,3260	2
Corrective	0,3137	3

The overall ranking for each maintenance strategy is presented in *Table 6* where the higher ranking represented by predictive maintenance strategy

6. Conclusion

This paper presents a multi-criteria decision making for evaluation of equipment maintenance strategies in the ships operational management. The integrated AHP and TOPSIS approach is proposed as an efficient and effective methodology to be used by decision makers. This method is simple to understand and permits the pursuing of best alternatives through the criterion which depict in a simple mathematical calculation. In this paper it is concluded that the Predictive Equipment Maintenance Strategies is the best in performance and is followed by Preventive and Corrective maintenance strategy. Taking into consideration all the different criteria of various strategies, the performance of Corrective Strategy is not good enough. It is notable that the subject Operational Endanger of Operational Degree is more valuable than the others and gives higher score when examining the overall evaluation methodology and is followed by Personnel selection criterion.

Due to strategic importance and the influence on ship operation, the maintenance process selection through extensive research is solved with this MCDM. On the other hand this two-step model can be applied reliably to the decision making situations where there are many options available and the criteria for the final decision are uncertain and ambiguous. This extensive research in ships could introduce an approach with ability to deal with uncertain criteria and with both qualitative and quantitative performance measures. Furthermore it will be applied to offshore structures selection problems where multiple and conflicting criteria are involved.

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