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Enhance of Ship Safety Based on Maintenance Strategies by Applying of Analytic Hierarchy Process

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Abstract

The equipment maintenance strategy is one of the factors influencing the safety and overall operational management of the ship. Using the wrong maintenance strategies can waste time, money, and resources, and often has no effect on improving or maintaining availability of equipments. Thus the reliability of the ship is reduced, and the risks and the probability of failures increased. The aim of this paper is to show one approach to the risk evaluation from equipments maintenance strategy of the ship. The paper describes main characteristics of Maintenance Strategies where the impact on safety is crucial and a model for evaluation of its risk. The model is based on the application of the Analytic Hierarchy Process method. The developed model uses subjectivity, experience and knowledge, when determining significance of selected risk elements in relation to total safety and risk.

JEL Classification: C670; C830.
Keywords: Maintenance Strategy; Ship Safety; Multi Decision Criteria Making; AHP.

1. Introduction

The constant process of globalization leads the competition among researchers and manufacturers. As a result they optimize the build quality, and the cost becomes more competitive for the environmental friendly structures. Furthermore, the majority of technical and commercial activities within shipping industries 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. The relevant organizations ensure the execution and implementation of international rules, regulations, and other requirements related to the safety and reliability under a unique scheme during the various activities in the boundaries of maritime transportation industry. The adoption of strict environmental standards, both in Europe and in the United States, is forcing shipping firms to reduce the emissions of pollutants from the process of the power production plants and reduce the potential pollution of the operations on ship.

Today 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 (Sarkar *et al.*, 2011) based on type of industry. Equally the increase of machinery quantity on ships and the complexed Ship 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 according to the inevitable cost of maintenance, to adopt maintenance strategies on equipments that are able to comply with demands on reliability, to increase the safety and finally at the lower possible cost.

A maintenance programme must be produced based on operational specific needs and objectives, taking into account the best practice. It is particularly difficult to choose the best mix of maintenance policies on a ship when needed to comply with many factors. The adoption of previous demands creates the need for the operators to select the best maintenance policy for each piece of equipment or system from a set of possible alternatives, for example, corrective, preventive, opportunistic, condition-based and predictive maintenance policies which are considered in this paper. This ensures the reliability and integrity of the structure, the systems and the equipments of a vessel, and through effective maintenance and management achieves today's fundamental safety and environmental performance standards. Hence the implementation of maintenance strategies is a vital practice for ship owners and operators. Especially while equipment maintenances are an obvious target when looking to reduce operating risk, and is widely accepted that effective maintenance strategies and appropriate repair will improve the reliability in the long run.

Thus, various attributes should be considered when selecting the type of maintenance and this selection must involve several aspects. Therefore the analysis and justification of maintenance strategy selection is a critical and complex task due to the great number of attributes to be considered, many of which are intangible.

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 (Almeida and Bohoris, 1995). Triantaphyllou *et al.* (1997) suggests the use of Analytical Hierarchy Process (AHP), 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 (Rausand, 1998). The proposals from literature and many others are considered in design and construction phase for land based industries, aircraft industry and later they adapted to several other industries (Al-Najjara and Alsyoufb, 2003, Wang *et al*., 2007, Sarkar *et al*., 2011).

This paper presents a method based on the AHP approach - AHP is a decision making technique, which enables the manipulation of both qualitative assessments, and quantitative metrics from estimations or recorded data in order to improve final judgments for selection of maintenance strategy (Dagkinis *et al*., 2012) to select the most appropriate maintenance strategy.

2. Maintenance strategy

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"* (British Standards Institution, 1974). If there is breakdown, swift actions must be taken to restore the equipment or facility to its "acceptable condition". Acceptable conditions will include those factors such as, Efficiency (fuel usage, power output, speed, etc.), Production of good quality product/ service, and Safety of operations.

With this definition, 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 management expertise includes: Engineering (design and construction), Management (scheduling, cost, information collection/analysis), and Accounting (profitability and investment in facilities).

The above factors were confirmed by an investigation carried out by the United Nations Industrial Development Organization (UNIDO) (United Nations Industrial Development Organization, 1971). In investigating the possibility of improving upon maintenance and repair practices in developing countries, a UNIDO report revealed that: *"The actual maintenance problem does not lie only in the actual repair operations but also in the planning and managerial activities at both the enterprise and the national levels"*.

It is clear that a good maintenance program 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.

2.1 Maintenance strategies

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 (Félix *et al*., 2006, Wang *et al*., 2007). The main characteristics of the 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. 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. 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.
- 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 at the Wharton School of Business 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 (Saaty, 1977). The AHP helps the decision makers to organize the critical aspects of a problem into a hierarchical structure similar to a chart of components depicted in boxes. The top box of chart represents the goal of the decision problem, and splitting in lower levels boxes represent an objective contributing to the goal. Each box can then be further decomposed into lower level boxes, which represent sub-objectives (Saaty, 1980, Saaty, 2008). And so on.

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 (i.e. the goal) through intermediate levels (criteria and sub-criteria on which subsequent levels depend) to the lowest level (i.e. the alternatives).

Then weight the criteria, sub-criteria and alternatives as a function of 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 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 (see Table 1). After a judgment matrix has been developed, a priority vector to weight the elements of the matrix is calculated. This is the normalized eigenvector of the matrix.

Table 1. Fundamental Scale of Absolute Numbers

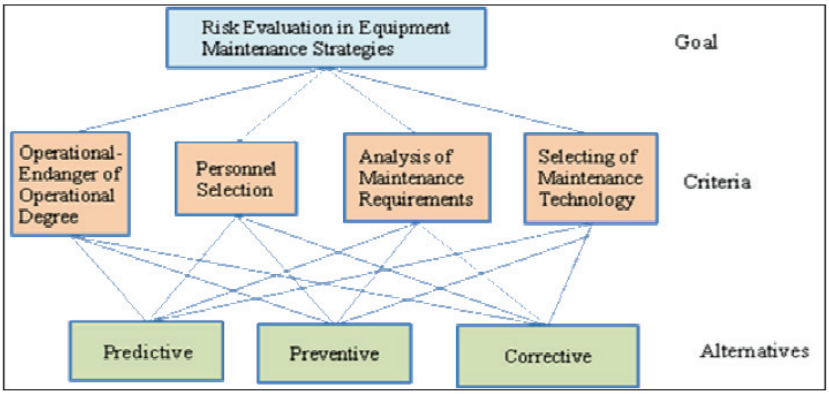
Intensity of importance	Value description	Explanation
1	Criterion i and criterion j are of equal importance.	Two activities contribute equally to the objective.
3	Criterion i is weakly more important than criterion j.	Experience and judgment slightly favor one activity over another.
5	Criterion i is strongly more important than criterion j.	Experience and judgment strongly favor one activity over another.
7	Criterion i is very strongly more important than criterion j.	An activity is strongly favored and its dominance demonstrated in practice.
9	Criterion i is absolutely more important than criterion j.	The evidence favoring one activity over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values between the two adjacent values.	When a compromise in judgment is needed.

Since we know the priorities of the Criteria with respect to the Goal, and the priorities of the Alternatives with respect to the Criteria, we can calculate the priorities of the Alternatives with respect to the Goal and finally synthesize 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.

4. The Development of a Hierarchical Decision Model

When developing the AHP hierarchical boxes chart (Fig. 1), the aim is to develop a general framework that satisfies the needs of the decision makers to solve the selection problem of the best maintenance strategy. The structure has been created by following suggestions from relevant equipment maintenances and working staff of shipping companies. 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 Fig. 1. These criteria then could break down into several sub-criteria.

Figure 1. The AHP Goal, Criteria and Alternatives



The circumscription of the hierarchy methodology that is described above has been developed using a brainstorming process (Bevilacqua and Braglia, 2000). Also the judgments of all the people concerned with maintenance problems in ship and onshore are included. In particular, in this study we include the opinions of maintenance engineering personnel (On Ship and Off Ship who perform the maintenance analyses and develop the maintenance improvement procedures), the operation personnel (who manages the maintenance operations) and the safety personnel (who performs the analysis of factor Operational Endanger Degree).

The relevant factors defining the Operational Endanger Degree criterion 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 propulsion power loss and electric power loss are linked to the ship's availability downtime derived from a failure, the time required for detection, repair or restoration to operating condition and re-starting, and they are related to the MTBF and MTTR. Moreover the propulsion failures, electric power failures and cargo handling facilities losses are divided to direct and indirect: the direct damage relates with the tangible effects of the failure on the machine, the indirect damage takes into account the possible influences of the failure on the system as a consequence of a "domino effect" on other facilities and instruments.

The risk of Personnel Selecting factor, concerns the importance of personnel selection. The optimal thought is on ship to have the best maintenance personnel for handling the maintenance. But is it possible in shipping industry to have the personnel with ability to inspect and repair the new equipment with the more and more complexity and introduction of new technology? The answer lies in the repairs policy followed by shipping company, where either the crew are more expensive but have wide experience and knowledge, or the crews are cheaper and repairs are performed by specialized teams that visit the ships for scheduled maintenances. Also 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, all these factors have different weight and influence for each one of the maintenance strategies at pairwise comparisons.

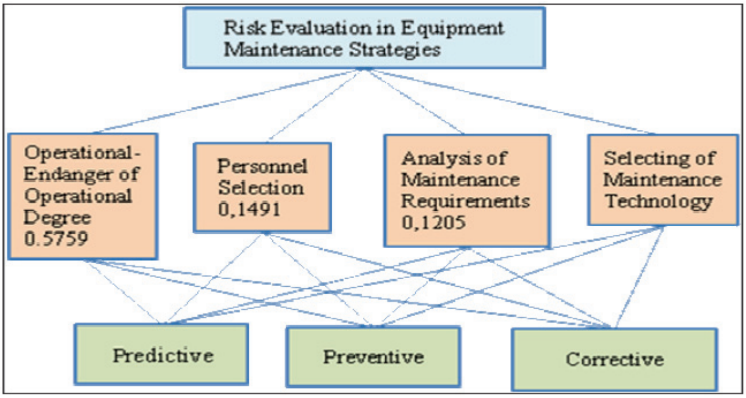
The criterion of Analysis of the Maintenance Requirements, takes into account the costs required for the strategy implementation and the availability of the machinery. This is described by the maintenance requirements based on the needs of the maintenance strategy, the funds available for a repair, the availability of a spare part or the logistics chain requirements to be delivered on the ship, the accessibility of the machine to be repaired, etc. The equipments in this case could be classified into categories in order to achieve the costs reduction of the spare parts i.e. in preventive maintenance strategy.

Selecting maintenance technology is another important criterion for a maintenance strategy implementation. With the development of technology, many advanced technologies have been integrated covering extensive fields, such as online performance analysis of equipments, the analysis of wear debris, accurate alignment and balance, sophisticated measuring instruments etc. All the above are related to the technical requirements, the survey program, the repairs, for the efficient operation of the ship. The Selecting maintenance technology achieves improvement of maintenance results and provides predictability of failures that could lead to total failure of a machine.

5. AHP Analysis and Results

The diagram in Fig. 2 shows the AHP hierarchy at the end of the decision making process. The goal is to choose the most suitable maintenance of Equipment Maintenance Strategies (EMS) to enhance the risk evaluation based on four specific criteria.

Figure 2. The AHP development and the global priority indices



The steering pump has been selected as a representative machine for the AHP analysis in this study. This pump belongs to machinery group 1 which is the group with bigger percentage of the ship machineries. A failure in a steering system can lead to serious consequences in crew safety, ship availability, and environment. As an overview, the steering gear on ships provides a movement of the rudder in response to a signal from the bridge. The total system consists of three parts, control equipment, a power unit and a transmission to the rudder stock. The control equipment conveys a signal of desired rudder angle from the bridge and activates the power unit and transmission system until the desired angle is reached. The power unit provides the force, when required and with immediate effect, to move the rudder to the desired angle. Steering gears can be arranged with hydraulic control equipment known as a 'telemeter', or with electrical control equipment. The power unit may in turn be hydraulic or electrically operated. Usually for seagoing vessels the power unit is hydraulic. Hence a pump is required in the hydraulic system which can immediately pump fluid in order to provide a hydraulic force that will move the rudder. Instant response does not allow time for the pump to be switched on and therefore a constantly running pump is required that will provide fluid only when required. For this reason the pumps which are installed with these features are the variable delivery pumps.

Once the hierarchy structure of the maintenance strategy decision making problem is defined every available data is imported. Then the analytic hierarchy process (AHP) mathematical solver runs to synthesize the results and normalize the values. The priorities for the alternatives are specified in respect to each of the decision criteria, and priorities for each of the criteria with respect to their importance in reaching the goal are calculated using pairwise comparisons. The comparisons of alternatives with respect to Endanger of Operational Degree given by the experts' judgments are shown in Table 2. Then they are processed through the AHP matrix and the priorities results are shown in Table 3.

Table 2. Alternatives compared with respect to Endanger of Operational Degree

Predictive	4	Preventive	1	Predictive is weakly more important than criterion to Preventive Maintenance. Weight: 4
Predictive	9	Corrective	1	Predictive is absolutely more important to Corrective Maintenance. Weight: 9
Preventive	7	Corrective	1	Preventive is very strongly more important to Corrective Maintenance. Weight: 7

Table 3. The transfer of weights to the matrix

Operational Endanger of Operational Degree	Predictive	Preventive	Corrective	Priority
Predictive	1	4	9	0,6939
Preventive	1/4	1	7	0,2533
Corrective	1/9	1/7	1	0,0528

The next steps are the pairs' comparison of alternatives with respect to Personnel Selecting, Analysis of the Maintenance Requirements and Selecting Maintenance Technology. The weights are transferred into the matrixes and solve the AHP. Then the criteria are compared with respect to reaching the goal and with pairwise comparisons, the higher ranking criterion is the one used to achieve the goal.

Table 4 shows the final ranking for the Steering Gear Pump. Based on the expert's choice of decision criteria, on their judgments about the relative importance of each, and on their judgments about maintenance strategy with respect to each of the criteria, Predictive, with a priority of 0.4591, is by far the most preferable maintenance strategy. Preventive maintenance strategy, with a priority of 0,2820, is second, and Corrective maintenance strategy, at 0,2588, is third. For the Steering Pump the predictive strategy is highly preferable with respect to the others because a failure has critical influence to the ship's safety. This is the reason of the small difference between the other strategies. Also Fig. 2 shows the global priority indices for each criterion and alternative included in the AHP hierarchy structure for the Steering Gear Pump.

Table 4. The results for choose the best alternative

	Priority with Respect to				
Maintenance strategy	**Risk to Endanger the Operational Degree**	**Risk from Personnel Selection**	**Risk from Analysis of Maintenance Requirements**	**Risk from Selecting of Maintenance Technology**	**GOAL**
Predictive	0,3996	0,0121	0,0125	0,0349	0,4591
Preventive	0,1459	0,0281	0,0291	0,0790	0,2820
Corrective	0,0304	0,1089	0,1129	0,0066	0,2588
Totals	0,5759	0,1491	0,1545	0,1205	1,0000

6. Conclusions

This paper describes one approach for Risk Evaluation in Equipment Maintenance Strategies EMS of seagoing ships. Through EMS and application of the AHP method, modeling of various risk aspects that influence total risk is enabled. In the model, each risk criterion weight is based on experts' opinion and is introduced in a matrix where it is calculated and synthesized with pairwise comparisons. The results of ranking of risk elements provides support to making decisions in order to prevent the influence of an improper maintenance strategy of a certain machine on total risk.

The results and satisfaction from choosing maintenance strategy of certain equipment derived by using the AHP method confirms that it can improve and represents an effective approach to arrive at making decisions.

Furthermore, considering that the responsible maintenance person can never be sure of the relative importance of decision making in the selection criteria when dealing the complex problem of a ship maintenance, the improvement of effectiveness of AHP methodology could be achieved by implementation of sensitivity analysis for more accurate results.

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