J Intell Manuf (2018) 29:519–531
https://doi.org/10.1007/s10845-015-1133-6

Hybrid MCDM based methodology for selecting the optimum maintenance strategy for ship machinery systems

Ikuobase Emovon[1,2] · Rosemary A. Norman[1] · Alan J. Murphy[1]

Received: 20 March 2015 / Accepted: 21 July 2015 / Published online: 30 July 2015

Abstract The key to achieving optimum ship system reliability and safety is to have a sound maintenance management system in place for mitigating or eliminating equipment/component failures. Maintenance has three key elements; risk assessment, maintenance strategy selection and the process of determining the optimal interval for the maintenance task. The optimisation of these three main elements of maintenance is what constitute a sound maintenance management system. One of the challenges that marine maintenance practitioners are faced with is the problem of maintenance selection for each equipment item of the ship machinery system. The decision making process involves utilising different conflicting decision criteria in selecting the optimum maintenance strategy from among multiple maintenance alternatives. In tackling such decision making problems the application of a multi-criteria decision making (MCDM) method is appropriate. Hence in this paper two hybrid MCDM methods; Delphi-AHP and Delphi-AHP-PROMETHEE, are presented for the selection of appropriate maintenance strategies for ship machinery systems and other related ship systems. A case study of a ship machinery system maintenance strategy selection problem is used to demonstrate the suitability of the proposed methods.

✉ Ikuobase Emovon
i.emovon@newcastle.ac.uk

Rosemary A. Norman
rose.norman@newcastle.ac.uk

Alan J. Murphy
a.j.murphy@newcastle.ac.uk

1 School of Marine Science and Technology, Newcastle University, Newcastle, UK

2 Marine Engineering Department, Federal University of Petroleum Resources, Effurun, Nigeria

Keywords Analytical hierarchy process · PROMETHEE · Delphi method · Maintenance strategy alternative · Machinery system

Introduction

The bulk of world commodities are transported by ocean going vessels and therefore the place of the shipping industry with regard to the growth of world GDP cannot be overemphasized. However ships are sometimes involved in accidents that can be catastrophic resulting in production loss and damage to the environment and personnel that may be irreversible. This not only impacts on the shipping companies but also negatively impacts on world GDP growth. From accident data analysis performed for data collected from 1994-1999 it was observed that over 50 % of these accidents were caused by machinery failures (Wang et al. 2005). In order to mitigate or eliminate unplanned downtime of ship systems due to machinery failure there is the need for a sound and effective maintenance scheme to be in place. This will increase vessel availability and at the same time reduce the system downtime and the chances of vessel accidents, minimising cost. Maintenance is a combination of activities aimed at restoring assets or keeping them in their original state. In recent years, the increasing complexity of multi-component plant systems has led to a corresponding complexity in maintenance activities (Arab et al. 2013), together with a rise in the required human resource and costs (Wang and Tsai 2014). One of the main challenges of maintenance management is the selection of the appropriate maintenance strategy for each equipment item in the system because not all maintenance strategies are applicable and cost effective for different components. Hence choosing the right maintenance strategy for the system will help maintain a balance between the system availability and cost of performing the maintenance. However when choosing the type of maintenance strategy for a ship machinery system or other complex related ship systems, several conflicting decision criteria must be taken into consideration such as cost, reliability, availability and safety. These make maintenance strategy selection problem analysis critical and complex and the investigation fundamental and justifiable (Bevilacqua and Braglia 2000). Despite the importance of the subject, there are not many studies that have dealt with with analysis and development of maintainance selection policy (Bertolini and Bevilacqua 2006).

Reliability Centered Maintenance (RCM) has been applied to a greater or lesser extent in the maritime industry i.e. the use of RCM logic diagrams to select the most appropriate maintenance strategy for different components of a system from the failure modes perspective (Conachey 2005; America Bureau of Shipping 2004). However the use of RCM is a very time consuming exercise and generally limited to some specific equipment (Waeyenbergh and Pintelon 2004). Another limitation of the RCM technique in selecting maintenance strategies is that it does not allow for ranking of maintenance alternatives such that the optimum solution can easily be selected.

This prompted Lazakis et al. (2012) to develop a maintenance strategy selection methodology based on the integration of fuzzy set theory and TOPSIS for the selection of the maintenance strategy for a Diesel Generator of a cruise ship. The maintenance strategy selection model the authors proposed compared three alternative maintenance strategies (corrective, preventive and predictive maintenance) against eight decision criteria: maintenance cost, efficiency/effectiveness, system reliability, management commitment, crew training, company investment, spare parts inventories and operation loss. From the analysis, condition based maintenance (CBM) was considered as the optimum maintenance strategy for the cruise ship diesel generator. However some doubts remain with regard to the practical use of the fuzzy approach because of the difficulty in testing and developing extensive sets of fuzzy rules (Zammori and Gabbrielli 2012; Braglia 2000). Additionally some important decision criteria such as applicability for maintenance strategy selection especially when dealing with the problem from the system failure modes perspective were not taken into account by Lazakis et al. (2012). In further work Lazakis and Olcer (2015) the authors aimed to improve the performance of the fuzzy TOPSIS methodology by integrating the analytical hierarchy process (AHP) into it. The AHP was introduced to assist in the weighting of the decision criteria. The result of the enhanced technique yielded preventive maintenance as the optimum maintenance strategy for the for ship diesel generator.

Goossens and Basten (2015) utilized AHP in the selection of maintenance strategies for naval ship systems. The authors involved three different groups within the industry in the decision making process namely: the shipbuilders, the owners/operators and the original equipment manufacturers (OEM). In selecting the optimal maintenance strategy for the ship system from three maintenance strategies; corrective, time/use-based maintenance and condition based maintenance, three level decision criteria were applied. The first level consisted of two decision criteria; the second level consisted of eight and the third level consisted of 29. From the analysed results, the maintenance strategy preferred by the shipbuilder, owner/operator and the OEM is condition based maintenance. However the structuring of the problem made it computationally intensive as it required formation and analysis of numerous pairwise judgements from experts.

Resobowo et al. (2014) also applied AHP in prioritizing the factors that affect military ship maintenance management. In this case the factors considered were; cost, availability, reliability, safety, human resource, operations, types of ship and ship characteristics. These factors were ranked using planned maintenance, preventive maintenance and routine maintenance as decision criteria. According to the authors the result of the analysis revealed that the most important factor is human resource. The major interest of the authors was to identify important factors for making maintenance decision and as such does not completely address the problem of maintenance strategy selection.

It is obvious that there is a need for a more systematic approach that can easily incorporate qualitatively and/or quantitatively the maintenance alternatives selection criteria for marine system applications. On this basis two hybrid MCDM techniques are proposed for maintenance strategy selection for ship machinery systems and other related ship systems in this paper. The two proposed techniques are: (1) an integrated Delphi-AHP methodology and (2) an integrated Delphi-AHP-PROMETHEE methodology. In the Delphi-AHP method, the Delphi technique is applied to scrutinise the decision criteria while the AHP technique is chosen for weight determination of the decision criteria and for ranking of the maintenance strategy alternatives. For the second proposed method, the Delphi technique is again applied for the purpose of screening the decision criteria while AHP and PROMETHEE are applied for decision criteria weight determination and ranking of maintenance strategy alternatives respectively.

The paper is organised as follows: "Maintenance strategies" section describes the various maintenance strategies for remedying failure modes of marine machinery systems; "Maintenance strategy selection decision criteria" section discusses the various criteria and sub-criteria for selection of a maintenance strategy; "Methodology" section presents the proposed methodology for selecting maintenance strategies; in "Case study of a marine diesel engine" section the case of the marine diesel engine is presented to demonstrate the proposed methodology. Finally the conclusion is presented in "Conclusion" section.

Maintenance strategies

Maintenance is defined as a combination of activities to retain a component in, or restore it to, a state in which it can perform its designated functions (Dhillon 2002). Generally there are three basic maintenance types which are applicable for maintenance of marine machinery systems and other related ship systems. They are discussed as follows:

1. Corrective maintenance (CM): also referred to as reactive maintenance in which a machine or system is allowed to fail before it is restored to its original state. This type of maintenance is usually effective for non-critical and low cost components and equipment (Pride 2008).
2. Preventive maintenance (PM): is defined as maintenance actions scheduled based on the statistical life of plant systems with the aims of preventing wear and degradation, extending useful life and mitigating the risk of catastrophic failure (Sullivan et al. 2004). It consists of activities such as the replacement and renewal of components, inspections, testing and checking of working parts during their operation which are performed at established intervals (Ebrahimipour et al. 2015). Traditionally plant managers rely on manufacturer's recommendation and experience to schedule maintenance activities. The major advantage of PM is its ability to increase the average equipment life and reduce the risk of catastrophic equipment failure (Sullivan et al. 2004). However the major limitation is that it results in unnecessary repair if the interval is not properly timed. Hence another possible limitation of PM is the difficulty in determining the optimum level of preventive maintenance and this may take years of data collection and analysis (Chen 1997).
3. Condition based maintenance (CBM): the condition of equipment is monitored to detect performance degradation. Different techniques such as vibration analysis, oil analysis and motor current analysis using varying diagnostic tools are used in monitoring plant equipment condition. There are two condition monitoring methods for marine machinery systems continuous and periodic monitoring. In the continuous condition monitoring approach the condition of an equipment item is permanently monitored. The limitation of this approach is that it is very expensive. The approach that is generally applied is periodic monitoring because it is more cost effective. In this approach condition monitoring of an equipment item is scheduled on a time basis. Mathematical models for determining the optimal interval for monitoring the condition of a system are generally developed based on system failure data. An example of such model is the maintenance optimization model developed by Chouikhi et al. (2014) that takes into consideration environmental degradation in determining an optimum inspection interval for a production system.

Maintenance strategy selection decision criteria

The selection of maintenance strategies for different components/equipment items of the marine machinery system, taking into consideration their distinct failure modes, is a complex task which usually involves multiple criteria. In this work, 22 decision criteria were identified for selecting maintenance strategies for marine machinery systems. This was done through a thorough literature survey and face to face interviews with marine engineering experts both in academia and maritime industries. The identified criteria were then subjected to screening through the use of the Delphi method in order to ascertain the criteria that are most essential for selecting maintenance strategies. The various criteria and sub-criteria considered in this study are as follows:

1. Cost: The various maintenance strategies for marine machinery maintenance have different cost consequences. The various components of cost that may vary for the different maintenance approaches are:
   (a) Spare parts inventories
   (b) Maintenance cost: Cost of equipment, materials and labour for each maintenance strategy.
   (c) Crew training cost
   (d) Equipment damage cost: The cost consequences of damage to plant system equipment as result of implementing each maintenance strategy.
2. Safety: The level of safety required is determined by the maritime industry and regulation bodies and is a key factor in selecting the maintenance strategy for the machinery system. Safety is viewed in terms of:
   (a) Personnel: Failure of some equipment/components can result in serious injury or death of personnel on board ship. In such cases the most effective maintenance strategy is applied irrespective of cost.
   (b) Equipment: In the event of failure of a particular component/equipment item, the question is how safe is the entire system. Greater attention is paid to parts that may result in severe damage to the system. A maintenance strategy that will reduce failure frequency to the lowest level is advisable.
   (c) Environment: Failure of some parts of the marine machinery system can result in serious environmental hazards. The maintenance strategy that will reduce

failure of a piece of equipment to the lowest level is generally considered appropriate.

3. Added value: The following factors describe the value that is added to the system or equipment as a result of the application of each of the maintenance strategy alternatives:
   (a) Minimisation of operational loss
   (b) Equipment reliability: The maintenance strategy that will yield the highest reliability is generally chosen especially for high risk components/equipment.
4. Applicability: This criterion describes the possibility of implementing each of the maintenance strategies in mitigating or eliminating failures of the marine machinery system. The following factors are measured in this criterion:
   (a) System failure characteristics**:** The component failure characteristics; wear-in failure, random and wear-out failure are a key factor in selecting the most appropriate maintenance strategy for plant equipment. For example, CBM is suitable for components with random failure patterns, provided there is an identifiable warning sign for measuring the condition of the component.
   (b) Available monetary resource: is a vital factor in determining the optimum maintenance strategy. For example if available finance for maintaining the system cannot incorporate CBM, the plant manager is left with no choice other than to exclude it irrespective of the benefits.
   (c) Equipment risk level: For very high risk equipment whose failure is usually catastrophic, CBM is usually preferred.

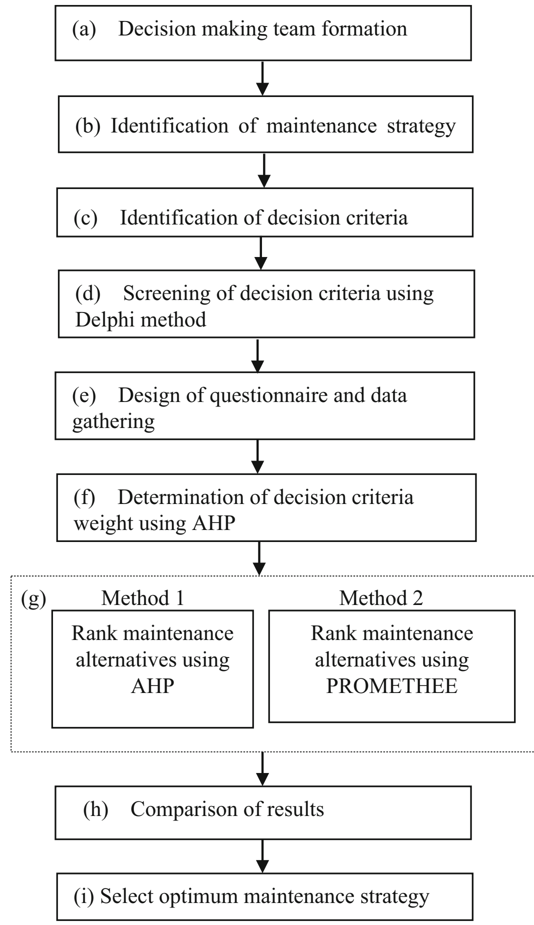

Fig. 1 Flowchart of proposed methods

Methodology

In this paper, two hybrid MCDM methods are proposed for selecting the maintenance strategy for a marine machinery system. The first method combines Delphi and AHP methods while the second method combines Delphi, AHP and PROMETHEE. Both methods use Delphi-AHP to screen decision criteria and determine their respective weights but then the first method uses AHP to rank the maintenance strategies whilst the second method uses PROMETHEE to implement this. The flow chart of the proposed methodology is presented in Fig. 1. The methodological steps are as follows:

Step (a): Decision making team formation: A team of experts is formed that will perform the selection of the optimum strategy for each equipment item/component of the system.

Step (b) and Step (c): The maintenance strategy alternatives and the decision criteria for selecting the alternatives are identified by the team based on experience and literature.

Step (d): The team use the Delphi method to carry out screening of the decision criteria such that the most significant criteria are identified for maintenance strategy alternatives.

Step (e): Two types of questionnaire are designed: The first questionnaire is designed for experts to carry out pairwise comparison judgment of decision criteria alongside pairwise comparison judgment of maintenance alternatives against decision criteria. The second type of questionnaire designed is based on a Likert scale; in this paper a 5 point Likert scale was applied to design the questionnaire for obtaining data for PROMETHEE.

Step (f): Determination of decision criteria weight: The pairwise comparison judgment obtained from the experts for the decision criteria is used as the input into the AHP evaluation technique to calculate weights of decision criteria.

Step (g): Ranking of alternatives: The maintenance strategy alternatives are ranked using AHP and PROMETHEE.

Step (h) and step (i): The ranking obtained from both methods are compared and an optimum strategy is then determined.

Delphi method

The Delphi method can be used to iteratively process opinions of experts until a consensus is reached on the subject under investigation (Delbecq et al. 1975). The development of the technique can be dated back to the early 1950s and a study conducted by the US Air Force-sponsored Rand Corporation (Linstone and Turoff 1975). In order to obtain high quality results from Delphi analysis, some authors have recommended a sample size of between 5 and 15 experts (Kim et al. 2013; Novakowski and Wellar 2008; Cavalli-Sforza and Ortolano 1984) The Delphi method has been applied standalone or in combination with other techniques in solving a variety of problems in the literature: Joshi et al. (2011) employed the Delphi technique in identifying, synthesizing and prioritising key performance factors of a refrigeration system; Kim et al. (2013) used the Delphi technique to identify objective evaluation criteria for selecting electronic waste to be recycled.

The first step in the Delphi methodology is to select a panel of experts to be used for the investigation. A questionnaire is then developed which could either have open ended or closed questions and this is sent to the panel of experts (first round Delphi survey). The next step is to analyse the results of the first round survey and send the result alongside the second round questionnaire, which is usually a modification of the first round questionnaire, to the experts (second round Delphi survey). The iteration continues until a consensus is reached among the experts for all items in the questionnaire; in most cases a consensus is reached at the second or third round.

Different authors have advocated various techniques to determine the overall opinions of all experts. Lawshe (1975) proposed a content validity ratio (CVR) with a threshold value defined for removing or retaining a criterion item. This was re-evaluated by Wilson et al. (2012), the model being as follows:

$$\mathrm{CVR} = \frac{\mathrm{N_{PE}} - (\mathrm{N}/2)}{\mathrm{N}/2} \quad (1)$$

where $\mathrm{N_{PE}}$ is the number of experts indicating an item is essential and N is the total number of panel experts. The value of CVR varies from +1 (all panel experts indicate an item is essential) to −1 (if all panel experts indicate an item is non-essential). The threshold value is generally set at greater than 0.29 and the implication is that any item with a CVR value greater than 0.29 is retained (Kim et al. 2013). Vidal et al. (2011) and Vidal et al. (2011) applied mean values in determining items to remove or retain and with this approach, items with a mean value below 4.5 on a 5 point Likert rating scale were removed. It is worth noting that the mean value of all expert ratings in this particular study was set at 2.7 since a 3 point Likert scale was used in designing the Delphi questionnaire. This is equivalent to the 4.5 threshold used by Vidal et al. (2011) and Vidal et al. (2011) on 5 point Likert scale.

Analytical hierarchy process (AHP)

AHP, first developed by Saaty (1980), is a widely used multi criteria decision making tool which helps decision makers to structure complex decision problems. AHP has been applied in solving numerous problems, for example, Akman et al. (2013) applied AHP within the fuzzy environment in the evaluation of innovative management strategies in different leading companies in Turkey. AHP has been chosen mainly because it provides a framework to manage conflicting multi-criteria problems involving both qualitative and quantitative facets. Additionally the quality of expert opinions involved in the process can be mathematically proven using the consistence index (Zammori and Gabbrielli 2012; Saaty 1980). However AHP has limitations one of the main ones being the computational complexity in the analysis process when the decision criteria for selecting alternatives is more than 15. This shortcoming of AHP is overcome in this paper by integrating the Delphi technique into the AHP method. AHP basically involves reducing complex decisions to a series of simple pairwise comparisons and rankings, and then synthesizing the results to obtain an overall ranking. The steps for AHP analysis, as presented in Caputo et al. (2013), with revision are as follows:

1. Define decision criteria C_i to be used to evaluate and prioritise maintenance alternatives. The criteria were defined using the Delphi study, see "Delphi evaluation" section.
2. Define maintenance alternatives to be prioritised. Three maintenance alternatives have been identified for mitigating effects of equipment failures of marine machinery systems.
3. Design the AHP questionnaire for k experts to perform pair-wise comparison of the relative importance among the n decision criteria. Each individual expert's judgements are then used to form an $n \times n$ pairwise comparison matrix, X^k represented as follows (Wu et al. 2008):

$$X^k = \left[x_{ij}^k\right]_{nxn} = \begin{bmatrix} x_{11}^k & x_{12}^k & \cdots & x_{1n}^k \\ x_{21}^k & x_{22}^k & \cdots & x_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1}^k & x_{n2}^k & \cdots & x_{nn}^k \end{bmatrix} \quad (2)$$

Table 1 Saaty scale (Saaty 1980)

Score	Relative importance
1	Criteria i and j are of equal importance
3	Criteria i is slightly more important than criterion j
5	Criteria i is significantly more important than criterion j
7	Criteria i is strongly more important than criterion j
9	Criteria i is extremely more important than criterion j

2, 4, 6 and 8 are intermediate values

where

$$x_{ij}^k > 0, x_{ij}^k = 1/x_{ji}^k, x_{ii}^k = 1$$

x_{ij}^k is the k-th expert defined rating of how the importance of criterion i compares with that of criterion j. For example if criteria i and j are of equal importance $x_{ij}^k = x_{ji}^k = 1$ and $k = 1, 2, \ldots,$ z. The AHP scale used in the ranking is presented in Table 1.

4. The weight to be assigned to criteria $C_{1,} C_{2,} \ldots, C_n$ is evaluated using the pair-wise comparison matrix X^k. The weights of each criterion are evaluated as follows:

$$w_i^k = \frac{1}{n} \sum_j \frac{x_{ij}^k}{\sum_i x_{ij}^k} \tag{3}$$

where w_i^k is the weight of criterion C_i
The weights of the criteria can be represented as weight vector ($\mathbf{W}^k$).

$$\mathbf{W^k} = \left[w_1^k, w_2^k, \ldots, w_n^k\right]^T \tag{4}$$

5. The consistency of judgement by the experts is then evaluated using the consistency ratio $I_{r,}$. In general a consistency ratio of less than 0.1 is acceptable and if the value is greater than this, experts should be advised to revise their initial judgement (Saaty 1980). The consistency ratio is calculated as:

$$I_{r,} = \frac{CI}{RI} \tag{5}$$

where RI is the corresponding average random value of CI for an nxn matrix and the values are shown in Table 2 and CI is the consistency index and can be evaluated as

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{6}$$

where $\lambda_{\max}$ is the maximum Eigenvalue

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{\left(Aw^k\right)_i}{w_i^k} \tag{7}$$

Table 2 RI values for different matrix order (Saaty 1980)

n	1	2	3	4	5	6	7
RI	0	0	0.52	0.89	1.11	1.25	1.35

6. The next step is to evaluate the local weight of each maintenance alternative for each criterion: firstly construct a pairwise comparison matrix between maintenance alternatives for each criterion using Eq. 2 (see a sample in Table 5), next the solution models used in evaluating criteria pairwise comparison of individual experts i.e. Eqs. 3–7 are also used for the maintenance alternatives pairwise comparison matrix to obtain local weight of each maintenance alternative.
7. The overall score of each maintenance alternative is evaluated by multiplying the local weight of a maintenance alternative by criteria local weight and summing over all criteria. Based on the overall score, maintenance alternatives are ranked and the most appropriate selected.
8. Where pairwise comparison judgements are available from more than one expert, the overall score of each maintenance alternative from individuals is averaged to obtain a group overall score for the maintenance alternative (Bolloju 2001).

PROMETHEE method

PROMETHEE is an acronym for Preference Ranking Organisation METHod for Enrichment Evaluations, a multi-criteria decision making method developed by Brans, first presented in 1982 (Brans 1986) and further extended by Brans and Vincke (Brans and Vincke (1985)). There have been 7 versions developed (Behzadian et al. 2010) and the one used here is PROMETHEE II. PROMETTHEE II is the most popular of the full versions and it's fundamental to the implementation of the other versions. The basic principle of PROMETHEE II for solving multi-criteria decision problems is the pairwise comparison of all alternatives for each criterion. The performance of one alternative over another in the pairwise comparison for each criterion is based on a preference function. This preference function (PF) turns the difference between two alternatives for each criterion into real values which range from 0 to 1. This corresponds to the degree of preference a maintenance practitioner has for one alternative over another. If the difference between two alternatives is 0, it simply means no preference and if the value is 1 its means full preference (Mareschal and De Smet 2009). There are six different types of preference function; usual criterion, U-shape criterion, Gaussian criterion, V-shape criterion V-shape with indifference and level criterion (Brans et al. 1986). For this paper the usual criterion was selected as the preference function because there is evidence in the literature that it is most suitable for qualitative data (VPSolution 2013).

Apart from the preference function that needs to be defined by the maintenance practitioners for the application of PROMETHEE, additional information that needs to be defined are the weights of the criteria. There are different techniques available for determining the weights of criteria such as the AHP method, entropy method and variance technique. The AHP technique was selected for this work as it enables the decision problem to be logically structured, a feature lacking in the PROMETHEE method. However AHP has the disadvantage of trading off assigned criteria "good" ratings for "bad" ratings and vice versa because its information evaluation principle is based on complete aggregation of the additive type which can result in loss of vital information. PROMETHEE however is based on the outranking technique or partial aggregation which is a better alternative to the complete aggregation technique due to the fact that the trade-off associated with the complete aggregation technique is avoided (Macharis et al. 2004). Additionally AHP has a predetermined technique for criteria weight evaluation whereas in the PROMETHEE technique there is no provision for criteria weight determination thereby laying an additional burden on the maintenance practitioners. On this basis, a combination of the two techniques, AHP-PROMETHEE, is proposed for the prioritisation of maintenance alternatives by utilising the areas of strength of each technique. While AHP is used in the structuring of the decision problem and weighting of decision criteria, PROMETHEE is applied in the ranking of the maintenance alternatives.

The basic steps of the PROMETHEE method can be defined as follows:

1. Definition of the problem: consider a multi-criteria problem of m alternatives $(a_1, a_2, \ldots, a_m)$ and n criteria $(c_1, c_2, \ldots c_n)$.
2. Determination of deviation based on pairwise comparisons as follows:

$$d_j(a,b) = c_j(a) - c_j(b) \tag{8}$$

   where d is the pairwise difference between evaluations of alternatives a and b for each criterion
3. Utilisation of preference function:

$$P_j(a,b) = F_j\left\{d_j(a,b)\right\} \tag{9}$$

   where $P(a,b)$ represents the preference of alternative a with respect to alternative b for each criterion, as a function of $d_j(a,b)$.
   If the usual criterion is chosen as the preference function then:

$$P_j(a,b) = \begin{bmatrix} 0 \text{ if } d_j(a,b) = 0 \\ 1 \text{ if } d_j(a,b) > 0 \end{bmatrix}$$

4. Define numerical weight of criteria: This is a measure of the relative importance of each criterion. w_j^k is the weight of criterion c_j. Different techniques are applied in evaluating weight of decision criteria. Yuguang et al. (2014) applied the entropy method while (Sharma and Balan 2013) utilised the TOPSIS technique. The AHP technique is utilised in this paper. The normalisation of the weight, if there is need for it, is carried out as follows:

$$\sum_j^n w_j^k = 1 \tag{10}$$

5. Evaluation of the overall preference index of a over b, $\pi(a,b)$: The the weighted average of all the preference functions P_j (a, b) for all criteria is mathematically defined as follows:

$$\pi(a,b) = \sum_{j=1}^n w_j^k P_j(a,b) \tag{11}$$

6. The net preference flows which are used in the measurement of the performance of each maintenance strategy alternative are then computed. The net flow ϕ is the difference between the positive flow $\emptyset^+$ and the negative flow $\emptyset^-$, evaluated as follows:

$$\emptyset^+(a) = \frac{1}{n-1}\sum_{b\neq a}\pi(a,b) \tag{12}$$

$$\emptyset^-(a) = \frac{1}{n-1}\sum_{b\neq a}\pi(b,a) \tag{13}$$

$$\phi(a) = \emptyset^+(a) - \emptyset^-(a) \tag{14}$$

The maintenance alternatives are ranked on the basis of the net flow and the higher the value the better the alternative. Having obtained the input information from experts, rather than manually solving the multi-criteria decision problem by applying Eqs. 8–14, Visual PROMETHEE, developed by Bertrand Mareschal (VPSolution 2013) was used in

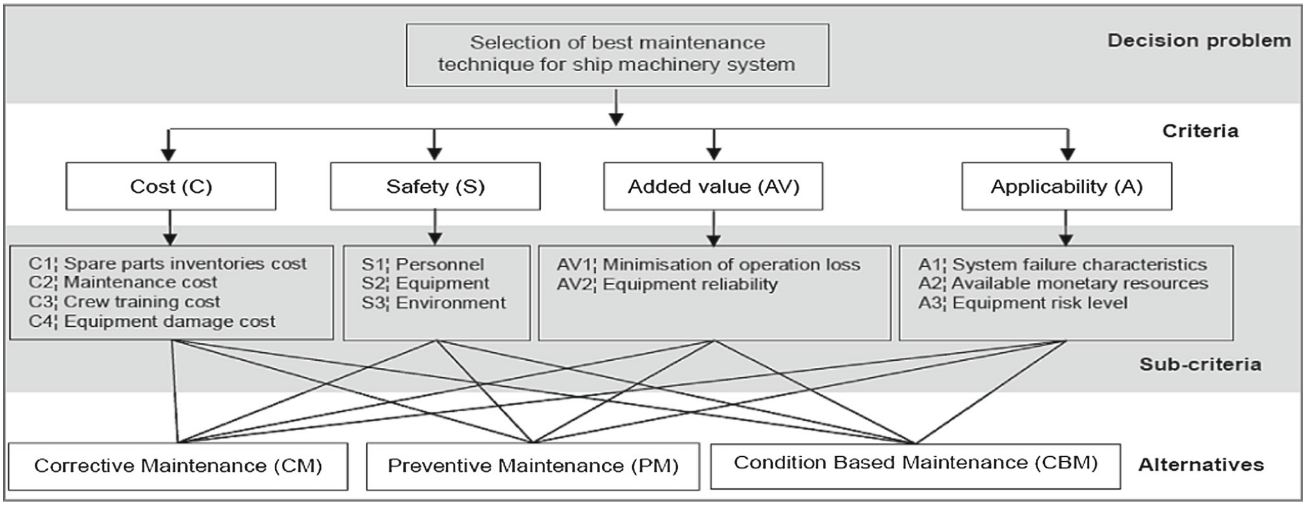

Fig. 2 AHP hierarchy of multi-criteria decision maintenance strategy selection problem

processing the information and in ranking the maintenance alternatives.

Case study of a marine diesel engine

The marine diesel engine is one of the most common prime movers for ship propulsion systems and its place in ship operations cannot be overemphasized. It consists of different systems such as the basic engine, fuel oil system and water cooling system. The prioritisation of risk of failure modes of the marine diesel engine has been carried out as part of ongoing research in the first phase of the RCM methodology (Emovon et al. 2014). From the study one of the equipment items with the greatest failure consequence on the marine diesel engine was found to be the high pressure pump of the fuel oil system. This high pressure pump is the heart of the fuel oil system which supplies high pressure fuel oil to the basic engine where it is converted into mechanical energy for ship propulsion. On this basis the high pressure pump was chosen to demonstrate the applicability of the proposed methodology in the selection of the maintenance strategy.

Delphi evaluation

A panel of ten experts was carefully selected, 5 from academia with 5–12 years previous work experience in the shipping industry and 5 from the shipping industry ranging from 2nd Engineer to Chief Engineer. Twenty two criteria were initially selected and these were subjected to two rounds of Delphi survey in order to critically select the most relevant evaluation criteria for selection of the maintenance strategy for maritime applications. The Delphi iteration process was terminated at the second round because there was no significant difference between the results of the first and second rounds. The consensus measurement index mean and CVR of all 10 experts' opinions were evaluated in the second round Delphi survey for each of the maintenance strategy selection criteria and the criteria with mean values below 2.7 and CVR below 0.29 were removed. Some other items were further removed because of their overlapping function with other criteria. The remaining criteria were then re-categorised into main and sub-criteria.

AHP analysis

The maintenance strategy selection criteria categorised into main and sub-criteria were then used to form a four level AHP hierarchy decision problem as shown in Fig. 2. With the first, second, third and fourth levels representing overall goal (Decision problem), main criteria, sub-criteria and the alternative maintenance strategy to be selected with respect to the main and sub criteria respectively.

To evaluate the problem in Fig. 2 a structured AHP questionnaire was developed and sent to one expert selected from the Delphi survey team to perform the pairwise comparison judgement using the Saaty ratio scale in Table 1, firstly for the main criteria with respect to the overall goal, next for the sub-criteria with respect to the main criteria and overall goal and lastly for the maintenance alternatives with respect to the sub-criteria. The comparison matrix developed from the expert judgement for main criteria is presented in Table 3. Samples of the sub-criteria and the maintenance alternatives comparison matrices are shown in Tables 4 and 5 respectively. The consistency of expert judgement in all scenarios measured using consistency ratio I_r was in the range of 0.00 to 0.084 which is within the acceptable value of less than 0.1.

Table 3 Main criteria comparison matrix with respect to overall goal

	C	S	AV	A
C	1	1/7	1/3	1/3
S	7	1	3	3
AV	3	1/3	1	1
A	3	1/3	1	1

Table 4 Sub-criteria comparison matrix with respect to main criterion (cost)

	C1	C2	C3	C4
C1	1	1/3	3	1/5
C2	3	1	3	1/3
C3	1/3	1/3	1	1/7
C4	5	3	7	1

Table 5 maintenance alternatives comparison matrix with respect to sub-criterion (spare parts inventories cost)

	CM	PM	CBM
CM	1	1/3	1/3
PM	3	1	1
CBM	3	1	1

The local weights of the main criteria were evaluated based on Table 3 using Eqs. 3–7 and the results are presented in Table 6. Equations 3–7 were also applied to Table 4 to obtain local weight of the sub-criteria and the result is also shown in Table 6.

The global weight of sub-criteria was generated by aggregating the local weight of main criteria and local weight of sub-criteria and the results are also presented in Table 6. Finally the overall score of maintenance alternatives was obtained by using step 7 of "Analytical hierarchy process (AHP)" section and the results are presented in Table 7.

Comparing the overall scores of the three alternative maintenance strategies in Table 7, condition based maintenance (CBM) with the highest performance index of 0.5720 is the preferred alternative followed by preventive maintenance (PM) with weight of 0.2838 and the least preferred is corrective maintenance (CM) with a priority value of 0.1390. The preferred choice of condition based maintenance for this maintenance decision problem using the proposed methodology is in line with the recent increase in the use of CBM for ship system critical equipment. The aim is to have a safer and a more reliable system and from this analysis as it can be seen in Table 6 that safety criteria have the greatest influence in the selection of the alternative maintenance strategies for the high pressure pump of the fuel oil system of a marine diesel engine with a weight of 54 % when compared to other main criteria such as cost, added value and applicability with weights of 6.9, 19.3 and 19.3 % respectively.

PROMETHEE 2 analysis

For the AHP technique information was obtained from experts through a pairwise comparison method in which two items were compared at a time in terms of the importance of one over the other using the Saaty scale for each criterion. However for the PROMETHEE analysis a 5 point Likert scale was applied in this study in obtaining information from experts. In order to have unbiased comparison of the PROMETHEE and APH techniques, the same experts that performed the pairwise comparison judgment were used in obtaining information for the PROMETHEE method. The assigned values for the three maintenance alternatives with respect to 12 decision criteria by a single expert using the 5 point Likert scale are shown in Table 8.

One of the reasons PROMETHEE is very popular is the availability of software to carry out the analysis and here Visual PROMETHEE was used in evaluating information obtained from the expert in Table 8 and the criteria weight generated from the AHP analysis in Table 7, for the purpose

Table 6 Local and aggregated (global) weight of criteria

Main criteria	Local weight	Sub-criteria	Local weight	Global weight
C	0.0690	C1	0.1240	0.0086
		C2	0.2410	0.0166
		C3	0.0650	0.0045
		C4	0.5700	0.0393
S	0.5400	S1	0.6000	0.3240
		S2	0.2000	0.1080
		S3	0.2000	0.1080
AV	0.1930	AV1	0.5000	0.0965
		AV2	0.5000	0.0965
A	0.1930	A1	0.3330	0.0643
		A2	0.3330	0.0643
		A3	0.3330	0.0643

Table 7 Maintenance strategies (alternatives) overall score

	CM	PM	CBM	Criteria global weight
C1	0.143	0.429	0.429	0.0086
C2	0.429	0.429	0.143	0.0166
C3	0.429	0.429	0.143	0.0045
C4	0.105	0.258	0.637	0.0393
S1	0.088	0.243	0.669	0.3240
S2	0.088	0.243	0.669	0.1080
S3	0.105	0.258	0.637	0.1080
AV1	0.088	0.243	0.669	0.0965
AV2	0.097	0.388	0.515	0.0965
A1	0.333	0.333	0.333	0.0643
A2	0.455	0.455	0.091	0.0643
A3	0.105	0.258	0.637	0.0643
Overall score	0.1390	0.2838	0.5720	

Table 8 Expert judgment of maintenance alternatives

Criteria	CM	PM	CBM
Spare parts inventories cost (C1)	1	3	5
Maintenance cost (C2)	2	3	4
Crew training cost (C3)	4	3	2
Equipment damage cost (C4)	1	3	5
Personnel (S1)	1	4	5
Equipment (S2)	1	3	5
Environment (S3)	1	3	5
Minimisation of operation loss (AV1)	1	3	5
Equipment reliability (AV2)	1	3	5
System failure characteristics (A1)	1	2	4
Available monetary resource (A2)	5	3	2
Equipment risk level (A3)	1	3	5

of determining the optimum maintenance alternative for the high pressure pump of the fuel oil system.

The decision matrix in Table 8 and the decision criteria weights obtained in the AHP analysis were then input into the PROMETHEE software to obtain the performance index of the three maintenance strategy alternatives. Prior to the analysis of the data in Table 8 with the PROMETHEE software, a preference function for each criterion was defined. In this study the preference function 'usual criterion' was chosen for each criterion because it is designed for use with a qualitative scale with fewer levels such as the 5 point Likert scale. After defining the preference function for each criterion, net flow which is the difference between positive flow and negative flow was obtained using Visual PROMETHEE. The results of the net flow, Φ, together with the positive flow, Φ^{+}, and negative flow, Φ^{-}, for the three maintenance alternatives are presented in Table 9.

Table 9 PROMETHEE flows (Φ) and ranks of maintenance strategy alternatives

Maintenance alternatives	Φ	Φ^{+}	Φ^{-}	Rank
CBM	0.8617	0.9308	0.0692	1
PM	0.0000	0.5000	0.5000	2
CM	−0.8617	0.0692	0.9308	3

The alternative with the highest value of net flow Φ is considered to be the best alternative while the alternative with the lowest value of net flow is the worst solution. From Table 9, CBM with the highest value of net flow is the best alternative, followed by PM and the worst alternative is CM. The values of net flow obtained in this case were based on the selection of the preference function referred to as 'usual criterion', these values would not be same if other preference functions were selected for the evaluation. Therefore obtaining a reliable and efficient result using the PROMETHEE technique depends greatly on the maintenance practitioner's ability to identify the appropriate preference function for each criterion. This creates an additional burden on the maintenance practitioner. Another factor that greatly impacts on the ranking is the weight of the criteria.

Comparison of methods

From the analysis, the order of preference for both techniques is CBM $>$ PM $>$ CM. A tool used for the measurement of the relationship between rankings obtained from different MCDM techniques is the Spearman rank correlation. Here the Spearman rank correlation coefficient between the two methods was evaluated to be 1. The perfect correlation between the two proposed methods shows that the two techniques can be used singly or in combination with one another for the purpose of prioritising maintenance strategy alternatives. This has also validated the applicability of the different MCDM techniques proposed for the selection of the maintenance strategy for the components of marine machinery systems from numerous alternatives.

Group decision making

The case considered above is a situation where by a single expert is involved in the decision making process. However in many practical situations multiple experts or a group of experts are involved in the decision making process thereby bringing a great deal of complexity into the use of MCDM methods (Raju et al. 2000). Different aggregation methods are available for combining experts' preferences in group decision making. Either rank or score aggregation can be used. In this research the score aggregation technique was chosen because rank aggregation may lead to rank reversal. In aggregating the scores of individual experts a simple arithmetic mean can be applied. The average of the individual experts AHP scores and PROMETHEE scores for each maintenance alternative are referred to here as group scores. On the basis of the group score, maintenance strategy alternatives were ranked and the highest ranked chosen as the optimum solution.

Evaluation of AHP group maintenance strategy alternatives

Three experts were involved in the decision making process as opposed to the single expert problem studied above. The result obtained for AHP in the single expert decision making process was taken as the expert 1 scores for the three maintenance strategy alternatives; CM, PM and CBM. Following the same AHP analysis process two further expert scores for maintenance strategy alternatives were obtained and the results are presented in Table 10.

To obtain the group score for each of the maintenance strategies, the individual expert scores were averaged as shown in Table 11. From this group result it is again obvious that the preferred maintenance strategy alternative is CBM having the highest group overall score of 0.5200. This is followed by PM and the least preferred choice is CM which has the lowest group score of 0.1977. There was no difference between the group rating and the individual expert rating in this case. This is in part due to the fact that only three alternatives were available making the degree of freedom limited. More alternatives would increase the likelihood of experts differing in rank order.

Table 10 Maintenance strategies overall score for expert 2 and 3

Experts	Maintenance alternatives		
	CM	PM	CBM
Expert 2	0.1860	0.2421	0.5707
Expert 3	0.2724	0.2070	0.5471

Evaluation of the PROMETHEE group maintenance strategy alternatives

The results obtained from the PROMETHEE analysis involving a single expert were again taken as the expert 1 scores. The same PROMETHEE methodological steps were then followed to obtain expert 2 and 3 scores for each of the maintenance strategies. The scores obtained for experts 2 and 3 are presented together with scores obtained previously for expert 1 in Table 12.

To obtain the group scores of maintenance strategy alternatives, the individual experts' scores were averaged, as also shown in Table 12. From the result, it is again obvious that the preferred maintenance strategy alternative is CBM, having the highest group overall score of 0.8132. This is followed by PM and the least preferred choice, CM having the lowest group overall score of −0.8120.

Comparison of the methods based on group decision making

From the AHP analysis and PROMETHEE analysis using three experts, the group scores obtained for the three maintenance strategy alternatives for the two techniques as presented in Tables 11 and 12 show that both techniques have the same preference order which is CBM > PM > CM. For the AHP analysis scores in Table 11, expert 3 had preference order as CBM > CM > PM as opposed to experts 1 and 2 with preference order of CBM > PM > CM. However for the PROMETHEE analysis result in Table 12 it can be observed the preference for the three maintenance strategy alternatives are the same. The result shows that the PROMETHEE technique is a more robust tool for ranking alternatives than AHP. This supports the claim that the outranking technique or partial aggregation (PROMETHEE) is a better alternative to the complete aggregation technique (AHP) (Macharis et al. 2004). The Spearman rank correlation was used to determine the relationship between the group rankings obtained from the two methods. It is obvious from the group ranking of maintenance alternatives that the Spearman rank correlation coefficient between the two MCDM techniques is 1. The same result was also obtained earlier when a single expert was used in the decision making process.

The perfect correlation between the two methods again shows that the two methods can effectively be applied as individual tools for the selection of marine machinery and other related system maintenance strategies. Furthermore,

Table 11 Group decision making AHP score

Maintenance alternatives	Expert 1 score	Expert 2 score	Expert 3 score	Group scores
CM	0.1347	0.1860	0.2724	0.1977
PM	0.2478	0.2421	0.2070	0.2323
CBM	0.4422	0.5707	0.5471	0.5200

Table 12 Group decision making PROMETHEE score

Maintenance alternatives	Expert 1 score	Expert 2 score	Expert 3 score	Group score
CM	−0.8617	−0.6712	−0.903	−0.812
PM	0.0000	0.0000	−0.0037	−0.0012
CBM	0.8617	0.6712	0.9067	0.8132

the resultant choice of CBM is in broad agreement with others that have used non-hybrid methods in the context of marine systems (Resobowo et al. 2014; Goossens and Basten 2015), whilst also overcoming the limitations of those methods as discussed in "Introduction" section.

Conclusion

In this paper, two hybrid MCDM techniques; (1) Delphi-AHP and (2) Delphi-AHP-PROMETHEE have been presented for the selection of a maintenance strategy for ship machinery systems. In the two proposed hybrid MCDM techniques, Delphi was applied in reducing the number of criteria such that only the most significant criteria were used in the maintenance alternative decision problem. The aim was to make the evaluation process as simple as possible such that it could easily be adopted by shipping system maintenance practitioners. AHP which has the capability of incorporating quantitative and qualitative information was used in the first proposed MCDM technique (Delphi-AHP) as a tool for determining the decision criteria weight and for the final ranking of the maintenance strategy alternatives with respect to decision criteria. In the second proposed MCDM technique (Delphi-AHP-PROMETHEE) AHP was applied as a tool for evaluating weights of decision criteria while PROMETHEE was used in the ranking of the maintenance strategy alternatives.

From the analysis the driving force for the selection of maintenance alternatives for critical ship machinery equipment is safety which was assigned half of the total weight of the decision criteria. The best ranked maintenance strategy alternative, CBM was considered the optimum maintenance alternative for the high pressure pump of the fuel oil system of the marine diesel engine. This is in line with the current shift from corrective maintenance and time-based preventive approaches for such critical ship system equipment to a safer and more reliable condition based maintenance approach. It is then obvious that the proposed methodologies can effectively be applied in selecting maintenance strategies for marine machinery systems and other related engineering systems.

Although AHP and PROMETHEE produced almost completely the same ranking result for the three maintenance strategy alternatives for the single expert and group decision making process, PROMETHEE would be recommended for those maintenance practitioners who may find generating numerous pairwise comparison judgments too laborious as compared to the use of a Likert scale that can be applied in generating data for PROMETHEE analysis.

References

Akman, G., Özcan, B., & Hatipoğlu, T. (2013). Fuzzy multi criteria decision making approach to innovative strategies based on miles and snow typology. *Journal of Intelligent Manufacturing*, *26*(3), 609–628.

America Bureau of Shipping, (2004). *Guidance note on reliability—Centered maintence*. New York: America Bureau of Shipping.

Arab, A., Ismail, N., & Lee, L. S. (2013). Maintenance scheduling incorporating dynamics of production system and real-time information from workstations. *Journal of Intelligent Manufacturing*, *24*, 695–705.

Behzadian, M., Kazemzadeh, R. B., Albadvi, A., & Aghdasi, M. (2010). PROMETHEE: A comprehensive literature review on methodologies and applications. *European Journal of Operational Research*, *200*, 198–215.

Bertolini, M., & Bevilacqua, M. (2006). A combined goal programming-AHP approach to maintenance selection problem. *Reliability Engineering and System Safety*, *91*(7), 839–848.

Bevilacqua, M., & Braglia, M. (2000). Analytic hierarchy process applied to maintenance strategy selection. *Reliability Engineering and System Safety*, *70*, 71–83.

Bolloju, N. (2001). Aggregation of analytic hierarchy process models based on similarities in decision makers' preferences. *European Journal of Operational Research*, *128*, 499–508.

Braglia, M. (2000). MAFMA: Multi-attribute failure mode analysis. *International Journal of Quality and Reliability Management*, *17*, 1017–1034.

Brans, J.-P. (1986). *L'élaboration d'instruments d'aide à la décision* (pp. 183–213). Raymond et Maurice Landry: Nadeau.

Brans, J.-P., & Vincke, P. (1985). Note–A preference ranking organisation method: (The PROMETHEE Method for Multiple Criteria Decision-Making). *Management Science*, *31*, 647–656.

Brans, J. P., Vincke, P., & Mareschal, B. (1986). How to select and how to rank projects: The Promethee method. *European Journal of Operational Research*, *24*, 228–238.
Caputo, A. C., Pelagagge, P. M., & Salini, P. (2013). AHP-based methodology for selecting safety devices of industrial machinery. *Safety Science*, *53*, 202–218.
Cavalli-Sforza, V., & Ortolano, L. (1984). Delphi forecasts of land use: Transportation interactions. *Journal of Transportation Engineering*, *110*, 324–339.
Chen, F. (1997). Issues in the continuous improvement process for preventive maintenance: Observations from Honda, Nippondenso and Toyota. *Production and Inventory Management Journal*, *38*, 13–16.
Chouikhi, H., Khatab, A., & Rezg, N. (2014). A condition-based maintenance policy for a production system under excessive environmental degradation. *Journal of Intelligent Manufacturing*, *25*, 727–737.
Conachey, R. M. (2005). *Development of machinery survey requirement based on Reliability-Centerd maintenance*. ABS Technical Papers.
Delbecq, A. L., Van De Ven, A. H., & Gustafson, D. H. (1975). *Group techniques for program planning: A guide to nominal group and Delphi processes*. Foresman Glenview, IL: Scott.
Dhillon, B. S. (2002). *Engineering maintenance: A modern approach*. Florida: CRC Press.
Ebrahimipour, V., Najjarbashi, A., & Sheikhalishahi, M. (2015). Multi-objective modeling for preventive maintenance scheduling in a multiple production line. *Journal of Intelligent Manufacturing*, *26*, 111–122.
Emovon, I., Norman, R. A., & Murphy, A. J. (2014). A new tool for prioritising the risk of failure modes for marine machinery systems. In: *Proceedings of the 33rd international conference on ocean, offshore and arctic engineering OMAE14, California United States*. Americal Society of Mechanical Engineers.
Goossens, A. J. M., & Basten, R. J. I. (2015). Exploring maintenance policy selection using the analytic hierarchy process: An application for naval ships. *Reliability Engineering and System Safety*, *142*, 31–41.
Joshi, R., Banwet, D. K., & Shankar, R. (2011). A Delphi-AHP-TOPSIS based benchmarking framework for performance improvement of a cold chain. *Expert Systems with Applications*, *38*, 10170–10182.
Kim, K. K., O'bryan, C. A., Crandall, P. G., Ricke, S. C., & Neal, J. A. (2013a). Identifying baseline food safety training practices for retail delis using the Delphi expert consensus method. *Food Control*, *32*, 55–62.
Kim, M., Jang, Y.-C., & Lee, S. (2013b). Application of Delphi-AHP methods to select the priorities of WEEE for recycling in a waste management decision-making tool. *Journal of Environmental Management*, *128*, 941–948.
Lawshe, C. H. (1975). A quantitative approach to content validity1. *Personnel psychology*, *28*, 563–575.
Lazakis, I. & Olcer, A. I. (2015). Selection of the best maintenance approach in the maritime industry under fuzzy multiple attribute group decision-making environment. *Proceedings of IMechE part M: Journal of Engineering for Maritime Environment*, 1–13. doi:10.1177/1475090215569819.
Lazakis, I., Turan, O. & Olcer, A. I. (2012). Determination of the optimum ship maintenance strategy through multi attribute decision making. In *11th International marine design conference*. Glasgow, UK: Scotland. pp. 473–487.
Linstone, H. H., & Turoff, M. (1975). *The Delphi method, techniques and applications*. London: Addison-Wesley.
Macharis, C., Springael, J., De Brucker, K., & Verbeke, A. (2004). PROMETHEE and AHP: The design of operational synergies in multicriteria analysis: Strengthening PROMETHEE with ideas of AHP. *European Journal of Operational Research*, *153*, 307–317.
Mareschal, B., & De Smet, Y. (2009). Visual PROMETHEE: Developments of the PROMETHEE and GAIA multicriteria decision aid methods. In *IEEE International conference on industrial engineering and engineering management*, 2009. IEEM 2009. IEEE, pp. 1646–1649.
Novakowski, N., & Wellar, B. (2008). Using the Delphi technique in normative planning research: Methodological design considerations. *Environment and Planning A*, *40*, 1485–1500.
Pride, A. (2008). Reliability centered maintenance. *Whole Building Design Guide* [Online].
Raju, K. S., Duckstein, L., & Arondel, C. (2000). Multicriterion analysis for sustainable water resources planning: A case study in Spain. *Water Resources Management*, *14*, 435–456.
Resobowo, D. S., Buda, K. A., & Dinariyana, A. A. B. (2014). Using sensitivity analysis for selecting of ship maintenance variables for improving reliability of military ship. *Academic Research International*, *5*, 127.
Saaty, T. L. (1980). *The Analytical Hierarchy Process*. New-york: McGraw-Hill.
Sharma, S., & Balan, S. (2013). An integrative supplier selection model using Taguchi loss function, TOPSIS and multi criteria goal programming. *Journal of Intelligent Manufacturing*, *24*, 1123–1130.
Sullivan, G. P., Pugh, R., Melendez, A. P., & Hunt, W. D. (2004). *Operations and maintenance best practices: A guide to achieving operational efficiency*. US: US Department of Energy.
Vidal, L.-A., Marle, F., & Bocquet, J.-C. (2011a). Using a Delphi process and the analytic hierarchy process (AHP) to evaluate the complexity of projects. *Expert Systems with Applications*, *38*, 5388–5405.
Vidal, L. A., Marle, F., & Bocquet, J. C. (2011b). Measuring project complexity using the analytic hierarchy process. *International Journal of Project Management*, *29*, 718–727.
Vpsolution (2013). Visual Promethee 1.4 Manual.
Waeyenbergh, G., & Pintelon, L. (2004). Maintenance concept development: A case study. *International Journal of Production Economics*, *89*, 395–405.
Wang, C.-H., & Tsai, S.-W. (2014). Optimizing bi-objective imperfect preventive maintenance model for series-parallel system using established hybrid genetic algorithm. *Journal of Intelligent Manufacturing*, *25*, 603–616.
Wang, J., Pillay, A., Kwon, Y. S., Wall, A. D., & Loughran, C. G. (2005). An analysis of fishing vessel accidents. *Accident Analysis and Prevention*, *37*, 1019–1024.
Wilson, F. R., Pan, W., & Schumsky, D. A. (2012). Recalculation of the critical values for Lawshe's content validity ratio. *Measurement and Evaluation in Counseling and Development*, *45*, 197–210.
Wu, W. H., Chiang, C. T., & Lin, C. T. (2008). Comparing the aggregation methods in the analytic hierarchy process when uniform distribution. *WSEAS Transactions on Business and Economics*, *5*(3), 74–80.
Yuguang, Z., Kai, X., & Dongyan, S. (2014). Clustering and group selection of interim product in shipbuilding. *Journal of Intelligent Manufacturing*, *25*, 1393–1401.
Zammori, F., & Gabbrielli, R. (2012). ANP/RPN: A multi criteria evaluation of the risk priority number. *Quality and Reliability Engineering International*, *28*, 85–104.