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Selection of the best maintenance approach in the maritime industry under fuzzy multiple attributive group decision-making environment

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Abstract

Many maintenance approaches have been developed and applied successfully in a variety of sectors such as aviation and nuclear industries over the years. Some of those have also been employed in the maritime industry such as condition-based maintenance; however, choosing the best maintenance approach has always been a big challenge due to the involvement of many attributes and alternatives which can also be associated with multiple experts and vague information. In order to accommodate these aspects, and as part of an overall novel Reliability and Criticality Based Maintenance strategy, an existing fuzzy multiple attributive group decision-making technique is employed in this study, which is further enhanced with the use of Analytical Hierarchy Process to obtain a better weighting of the maintenance attributes used. The fuzzy multiple attributive group decision-making technique has three distinctive stages, namely rating, aggregation and selection in which multiple experts' subjective judgments are processed and aggregated to be able to arrive at a ranking for a finite number of maintenance options. To demonstrate the applicability in a real-life industrial context, the technique is exemplified by selecting the best maintenance approach for shipboard equipment such as the diesel generator system of a vessel. The results denote that preventive maintenance is the best approach closely followed by predictive maintenance, thus steering away from the ship corrective maintenance framework and increasing overall ship system reliability and availability.

Keywords

Maintenance, maritime industry, Fuzzy Multiple Attributive Group Decision-Making, Analytical Hierarchy Process, diesel generator system

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Introduction

While the maritime industry is responsible for the massive transportation of goods worldwide, it is only recently that new approaches looking into the enhancement of ship's reliability, availability and accordingly profitability have been investigated. Ship maintenance accounting for 20%–30% of a ship's operational expenses has been so far related to downtime and financial burden in terms of unexpected ship repairs and loss of operational availability and accordingly income. In this case, one needs to consider the implementation of an overall maintenance strategy including a number of parameters indispensable to the overall maintenance implementation onboard ships. These parameters are related to the prevailing shipping company maintenance management commitment/approach, the cost of spare parts available onboard the ship, the company investment on novel maintenance tools (e.g. permanent installed/hand-held condition monitoring equipment), the cost for crew training on new maintenance shipboard applications and the overall increase in the ship system reliability as a result of a well-maintained ship.

In this respect, a number of existing maintenance approaches implemented in various industrial settings are initially investigated. These refer to the

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Terotechnology model, Integrated Logistic Support (ILS) and Logistic Support Analysis (LSA), Business Centred Maintenance (BCM), Asset Management (AM), Total Productive Maintenance (TPM), Risk-Based Inspection (RBI), Risk-Based Maintenance (RBM), and Reliability Centred Maintenance (RCM) among others addressing maintenance in various settings. Based on the above, by initially examining each one of these approaches, a clear insight of the existing industrial maintenance framework is developed which can provide the background for the creation and application of an innovative maintenance strategy for the maritime domain, namely the Reliability and Criticality Based Maintenance (RCBM) approach. RCBM key features are associated with the management characteristics of a shipping company's operation as well as the in-depth technical analysis of maintenance reliability and criticality aspects of ship systems and equipment. In this respect, RCBM can employ a number of tools in order to assess the reliability and criticality of ship systems and components. A particular one presented in this article is the one combining the benefits of Fuzzy Set Theory (FST) and Analytical Hierarchy Process (AHP) in order to come up with the best solution in a fuzzy multiple attributive group decision-making (FMAGDM) maintenance problem. The latter is originally described through a given number of maintenance-related attributes leading to a number of maintenance alternatives out of which the group of decision makers may select the best one. FST is employed in combination with AHP as it enables the use of information, which may be vague and imprecise to consider in the first place, while AHP assists in the initial ranking of weighting factors for a number of different attributes. AHP was first proposed by Saaty[1] and was applied in many decision-making studies in the maritime industry so far.[2–7] The hierarchical structure of attributes in the AHP model enables all group members of decision-making to visualise the problem systematically in terms of relevant attributes and sub-attributes.

Having mentioned the above, this article demonstrates the application of a novel approach to the multi-attributive group decision-making maintenance problem in the maritime industry. Section 'Literature review – maintenance methodologies' provides a background review regarding various maintenance methodologies and approaches currently in place. Section 'Methodology' presents the novel FMAGDM approach with the use of FST and AHP, while section 'Case study: DG system maintenance of a motor sailing cruise vessel' shows the applicability of the mentioned methodology in the selection of the best maintenance strategy for a diesel generator (DG) system of a motor cruise vessel. Verification and sensitivity analysis of the results takes place in section 'Case study: DG system maintenance of a motor sailing cruise vessel' too. Finally, section 'Conclusion' concludes this article with the discussion and final remarks.

Literature review – maintenance methodologies

Since the beginning of a systematic approach into ship repairs and maintenance, corrective maintenance was introduced as a first means of immediate response to ship structures and machinery upkeep. As the name suggests, this approach refers to a 'run-to-failure' state of components and ship systems. On the other hand, it does not consider the downtime originating from unexpected failures, moreover leading to expensive repairs and loss of productive trading time. Extending the scope of maintenance, preventive tasks were introduced next following predefined/planned maintenance intervals according to manufacturers' guidelines and requirements while also reporting non-conformities and keeping track of all maintenance and repair actions.

In this respect, various preventive maintenance methodologies have been presented in the past as far back as the 1970s. Initially, the Terotechnology model was introduced in the UK manufacturing industry to assess the interrelation among maintenance costs, productivity and overall profits.[8] In this context, the Terotechnology model focuses on the maintainability concept, thus the design and operation of physical assets and products in order to improve repair and maintenance.[9] ILS and LSA are also more of management concepts, which include maintenance as part of their activities for improvement.[10] Mostly related to the military sector, ILS and LSA refer to complex industrial and maintenance organisations, which on the other hand restrict them from being flexible enough to be applied in the ever-changing environment of the maritime industry.

BCM on the other hand includes maintenance optimisation as part of the entire business strategy.[11] BCM takes into account the business objectives for a specific system/organisation and ways on how to maximise profitability. However, BCM may become very extensive and complicated, thus requiring extensive use of resources including personnel and finances. In a similar context, AM addresses a 'better and more business focused maintenance' combining risk-controlled, optimised, life-cycle management of an asset.[12] Business objectives are at the core of this approach too as shown in the PAS55 and ISO55000 standards on the specifications for the optimised management of physical assets.[13,14] In this respect, although AM suggests the optimisation of the maintenance effort and cost, it pertains to organisations with considerable financial and human resources and high profit margins (e.g. oil and gas, power supply).

On top of the above, TPM addresses maintenance in the context of the entire management process.[15] TPM focuses on the increase of the Overall Equipment Effectiveness (OEE) by minimising the 'six big losses' such as breakdowns, setup and adjustment time, small stops, reduced speed, quality defects and start-up losses.[16,17] The latter is in line with Bohoris et al.,[18] which present the application of TPM in an automobile plant in UK. The difficulties in TPM implementation, that is, the lack of multi-tasked and autonomous maintenance groups, is also discussed in Cooke[19] and Chan et al.,[20] who identified 'organisational barriers' which may impede the successful application of TPM. Moreover, the maritime operational environment is directly influenced and linked to what Alsyouf[21] and Arca and Prado[22] suggest about the participation and competence of the human element as an essential factor for successful implementation of any maintenance approach. The latter could not be more relevant in the shipping industry as it is an industrial sector formulated out of a vast number of shipping companies operating with multinational crews.

Having in mind the above, predictive maintenance followed next as a step further into the enhancement of the condition of a system by optimising maintenance intervals, extending system operational life and reducing cost of repairs and maintenance. In this case, RBI and RBM take into account the consideration of a risk element as shown in Khan et al.[23] who present a RBI and maintenance system for the oil and gas industry to calculate the risk in the operation of onshore oil plants. Likewise, Patel[24] also discussed the application of RBI in the onshore oil and gas industry and suggested that the actual use of RBI lies within the inspection optimisation sequence. However, to the authors' opinion, this is a development which still lacks the element of the reliability and criticality evaluation of the system and its components.

CBM and accordingly Vibration-Based Maintenance (VBM) investigate the condition-based approach to the overall maintenance characteristics of a subject system. In Tsang et al.,[25] the various condition monitoring techniques are mentioned such as lube oil analysis of main and auxiliary engines, infrared scanning of electrical equipment, performance testing of pumps and heat exchangers, and vibration monitoring of rotating machinery. As Ross[26] also states, CBM is a maintenance approach that identifies problems before they take place as well as avoids needless time-based replacement. However, CBM and VBM are not currently employed in the maritime industry to a large extent as they are considered a much specialised type of maintenance.

RCM on the other hand originates from the review of the civil aviation preventive maintenance programme[27] through the Maintenance Steering Group handbook. Moreover, an updated RCM version considering the maintenance impact on the environment was presented by Moubray.[28] In terms of RCM applications, Fonseca and Knapp[29] demonstrated the combination of RCM with a software package in the chemical process industry, while Gabbar et al.[30] combined RCM with a Computerised Maintenance Management System (CMMS) in the case of a waterfeed process of a nuclear power plant, and Rausand and Vatn[31] demonstrated an RCM application in the railway sector. Although it is clear from the above cases that RCM is a widely applied methodology, it may become challenging to implement in the case of complex systems (e.g. military systems[9]). Furthermore, the company's top management support in the various tasks involved during RCM employment is highly required together with the need of extensive use of resources. Moreover, RCM is only considered as part of the overall integrated maintenance regime. It is this last remark which highlights a significant RCM shortcoming, that is the lack of an overall maintenance management system which will be flexible enough to suit each specific company/ship in the maritime domain. In the light of the above approaches and methodologies presented, Table 1 summarises the advantages and shortcomings of the mentioned maintenance approaches together with the gaps identified. These will assist further in the introduction of the novel RCBM strategy applied in the maritime industry as shown in the next section.

Methodology

Considering the above, the novel RCBM strategy eliminates the gaps, which are inherent to current maritime maintenance practices and methodologies, by proposing a number of intrinsic features. It suggests a holistic maintenance approach while it integrates the enhanced technical and management aspects in the maritime context through the coordination of the current planned maintenance regime with condition monitoring assessment, data acquisition and processing; also incorporating reliability and criticality analysis and decision support platforms. Furthermore, RCBM provides the framework for selecting the best maintenance approach for a specific ship or ship system, given the knowledge about its reliability and criticality characteristics and component functional relationships. Taking into account that the RCBM strategy has been described in detail in Lazakis[32] at both micro[33] and macro level,[34] the present article focuses on the application of RCBM using FMAGDM technique for selecting the best maintenance strategy having in mind a specific ship system. The FMAGDM technique combines FST with AHP in order to assist in the selection of the best maintenance approach for a ship system when a group of multiple decision makers with different backgrounds, expertise and preferences is involved.

FST was initially introduced by Zadeh[35] in order to address the fuzziness of imprecise answers to questions being asked. Since then, there have been various researchers updating the original FST concept including Zimmermann,[36] Chen and Hwang[37] and Ross[38] among others. FST considers a variety of different solutions/alternatives with vague and imprecise characteristics to choose from, while attributes can be assigned crisp or fuzzy (linguistic) values. A broad field of

Table 1. Advantages and shortcomings of the application of various maintenance approaches and gaps identified.

	Approach	Advantages	Shortcomings	Identified gaps
Corrective maintenance		One-off replacements, minimal repairs, minimum cost on spares	May lead to major unexpected failures, severe downtime, excessive repair cost	Lack of maintenance scheduling, non-optimum use of resources
Preventive maintenance	Terotechnology	Managerial framework, maintainability (design oriented), refers to complex organisations	Not maintenance oriented, maintenance considered as a by-product of the overall approach, not technically oriented	Maintenance not considered as a profit-generating area, restricted to a general procedural framework
	ILS/LSA	Life cycle cost approach, system design process, aims at minimising cost elements, refers to complex organisations	Maintenance is a small part of the overall approach, not flexible enough, not technically oriented	Lack of flexibility and supportability to suit every company, technical details on application missing
	AM	Business oriented, safety and environment focused, refers to complex organizations	Maintenance is a small part of the overall approach, not suitable for small–medium size companies, time consuming	Lack of flexibility and supportability to suit every company, too complex and time consuming
	TPM	Managerial framework, preventive maintenance oriented, minimise cost elements ('six big losses'), incorporate all departments within company, design oriented	Maintenance is a small part of the overall management 'picture', can easily become complicated and time consuming, no specific maintenance measures suggested	Lack of profit-generated aspect of maintenance, human resources management missing, organisational barriers, lack of technical aspect
	BCM	Business oriented, aims at maximising profitability, refers to complex organisations, data intensive	Maintenance is a small part of the overall approach, refer to complex organisations, extensive use of resources, time consuming	Business objectives considered, complicated to implement, lack of direct maintenance involvement
Predictive maintenance	RBI	Safety and risk-based approach, technically structured versus previous approaches	Missing reliability and criticality evaluation	Lack of criticality evaluation of system and components, limited application in maritime industry
	VBM/CBM	Advanced and technically detailed approach	Potential high capital cost/ investment, part of the overall solution	Minor application in maritime industry, not supporting full maintenance framework
	RCM	Thorough description of system and components, cooperation of various departments within company, maintenance database, cost minimisation	Extensive use of resources, can be time consuming, cost implications if too detailed, no feedback loop available	Lack of management aspect, managerial involvement required, close feedback loop needed

ILS: Integrated Logistic Support; LSA: Logistic Support Analysis; AM: Asset Management; TPM: Total Productive Maintenance; BCM: Business Centred Maintenance; RBI: Risk-Based Inspection; VBM: Vibration-Based Maintenance; CBM: condition-based maintenance; RCM: Reliability Centred Maintenance.

applications include studies from Wang et al.[39] who address the issue of selecting the best maintenance approach for a power generation plant, Yuniarto and Labib[40] who employ a decision-making grid to prioritise maintenance strategies for the operation of different systems. On the other hand, Carasco et al.[41] suggest that expert systems have some disadvantages such as inconsistent questions asked (input) and subsequently wrong responses and solutions (output) suggested. In the maritime industry, Riahi et al.[42] examined the application of FST in investigating seafarers' reliability. Ölçer and Odabasi[43] also applied FST for the selection of the best propulsion/manoeuvring system of a passenger vessel. Moreover, Gaonkar et al.[5] studied the condition monitoring of a ship turbine, while Nwaoha et al.[44] elaborated on the risk analysis and control of a liquefied natural gas ship.

AHP was initially developed by Saaty in the 1980s, while a number of studies have shown its applicability in different operational environments. In this respect, Labib et al.[45] developed a model on maintenance decision-making considering AHP and FST for an automotive plant reducing downtime considerably, while Mansor et al.[46] examined the application of AHP in the manufacturing process of passenger vehicles brakes system. Additionally, An et al.[47] presented a risk management model employing fuzzy AHP in the decision-making regarding an application in the railways domain, while Arslan and Turan[48] also explored the use of AHP in the case of the analytical investigation of maritime accidents in busy and narrow shipping crossings.

The suggested FMAGDM technique[43] as part of the RCBM strategy consists of three major parts: the rating, aggregation and finally the selection stages. It should be noted that the chosen FMAGDM technique is improved through the use of AHP in calculating the weights of attributes in this study. The suggested FMAGDM approach is initiated with the setting up a specific objective under which the decision-making will take place, that is the initial question that needs to be answered by a group of experts. This is followed by the three distinctive stages, which form the core of the FMAGDM approach; that is the rating, aggregation and selection stage. In the next paragraphs, each one of these stages is described followed by the specific application with regard to the selection of the most appropriate maintenance approach for the DG system of a given vessel. The reader is referred to Ölçer and Odabasi[43] for the details of the mathematical treatment of the FMAGDM technique used in this research.

Rating stage

The rating stage is the first part of FMAGDM in which specific attributes, which are originally instructed by the decision maker, as well as the specific number/group of experts that will participate in the FMAGDM process are determined. Overall, there are two types of attributes, which can be utilised: subjective and objective ones. The differentiation is that an objective attribute is described with crisp (numerical) values. That is because crisp values can be expressed in a numerical way for all experts involved (i.e. these values can be acknowledged as common and standard values). On the other hand, whenever an attribute is described in a vague (fuzzy) way including experts' subjective linguistic terms, then it is defined as a subjective attribute. Furthermore, both attribute types mentioned above can also be categorised according to the positive or negative linguistic value each attribute conveys. Therefore, they can be categorised as 'benefit' (positive linguistic meaning) or 'cost' (negative linguistic meaning). An example of benefit- and cost-type attributes is the 'maintenance efficiency' attribute, which is sorted as a benefit type of attribute, while 'company investment' is categorised as a cost-type attribute (the less the better).

Following the above, each one of the attributes and the experts are assigned weighting factors according to the relevance importance of the experts to the objective in question. When the experts are assigned similar weighting factors, the group decision-making problem is of a homogeneous nature, while when the experts' weighting varies, it is of a heterogeneous type. The alternatives (or solutions) for the maintenance type to be used are also provided at this stage. Subsequently, each expert provides an initial assessment on each alternative on the initial objective/question relevant to the various attributes. In other terms, the expert answers the questions deriving from the attributes of each solution (in this case maintenance type) and assigns crisp or linguistic terms (qualitative information) to them. The specific set of questions are provided by the facilitator of the decision-making process in the first place. In this way, the initial decision matrix for the FMAGDM selection is established.

What follows next is the transformation of the linguistic expression of the experts' answers to the initial fuzzy numerical expression. This is achieved by employing a set of different scales for transforming linguistic terms/answers to fuzzy trapezoidal numbers. The scales used are the ones suggested by Chen and Hwang,[37] which propose a set of eight different scales for the transformation of the fuzzy linguistic expressions to fuzzy numerical expressions. These scales vary from the simple ones using just two linguistic terms (Scale 1 – 'medium' and 'high' linguistic values) to the more complicated ones using 13 different linguistic terms (Scale 8).

Aggregation and selection stages

At this stage, all the answers given by the experts for each one of the suggested alternatives concerning each single subjective attribute used in the previous stage are aggregated. This is carried out in order to generate the set of fuzzy numbers for each one of the subjective attributes for all alternatives suggested that would be used in the defuzzification sub-stage.

After finalising the aggregation stage of the FMAGDM process, the selection stage is introduced next. This is compiled by two separate sub-stages: the defuzzification and eventually the selection of the best alternative sub-stage, which are described in the following section.

The first step in the selection stage is the defuzzification. This is performed so as to transform the aggregated fuzzy trapezoidal numbers into crisp numbers, which can then be used in the final selection stage of the best alternative available. In order to carry out the above, the fuzzy scoring method is employed as described in Chen and Hwang.[37]

In this way, the defuzzification stage is now concluded, enabling the transmission to the next step of the selection stage of the FMAGDM approach, which is the ranking sub-stage. In this case, the Technique Ordered Preference by Similarity to Ideal Solution (TOPSIS) method is used in this study as shown next.

Ranking using TOPSIS method

The most powerful and widely applicable is the TOPSIS method.[49,50] TOPSIS applicability is based on the ranking of each suggested alternative according to how close these are to an imaginary ideal positive solution and at the same time how far from an imaginary ideal negative solution. Subsequently, the alternative that is closer (or more similar) to the ideal positive solution and further from (or not similar to) the ideal negative solution is the one ranked higher than the other solutions and accordingly is the best one for the decision maker to choose.

In order to carry out the TOPSIS ranking method, the normalised ratings are calculated first using the vector normalisation technique for the r_{ji} element of the normalised decision matrix as follows

$$r_{ji} = \frac{x_{ji}}{\sqrt{\sum_{j=1}^{N} x_{ji}^2}} \tag{1}$$

where $j = 1, 2,..., N$; $i = 1, 2,..., K$ and x_{ji} = value of alternative j with respect to attribute i.

Then the weighted normalised ratings u_{ji} are calculated as the product of each row r_{ji} of the normalised decision matrix shown before and the weight w_i of each attribute as shown next

$$u_{ji} = w_i \, r_{ji} \tag{2}$$

where $j = 1, 2,..., N$; $i = 1, 2,..., K$ and w_i = weight of ith attribute.

As mentioned above, AHP is used for the calculation of the weights of attributes (w_i) due to the fact that it enables us to decompose attributes into several levels and it provides more correct values of weights.

In the following steps, the imaginary ideal solution is identified, that is the positive (A^+) and negative (A^-) ideal solution, respectively, which are defined as

$$A^+(E_u) = \left\{v_1^+, v_2^+, \ldots v_i^+, \ldots v_k^+\right\} \tag{3}$$

and

$$A^-(E_u) = \left\{v_1^-, v_2^-, \ldots v_i^-, \ldots v_k^-\right\} \tag{4}$$

where

$$v_1^+ = \left\{\max v_{ji},\ i \in J_1;\ \min v_{ji}\, i \in J_2\right\}$$

$$v_1^- = \left\{\min v_{ji},\ i \in J_1;\ \max v_{ji}\, i \in J_2\right\}$$

where J_1 is set of benefit attributes and J_2 is set of cost attributes.

The final ranking is performed by calculating the distance of each alternative from the ideal positive and negative values estimated in the previous step, that is, the distance S_i^+ from the positive ideal value and the distance S_i^- from the negative ideal value. This is performed using the following formulas

$$S_i^+ \sqrt{\sum_{i=1}^{K} \left(v_{ji} - v_1^+\right)^2} \tag{5}$$

$$S_i^- \sqrt{\sum_{i=1}^{K} \left(v_{ji} - v_1^-\right)^2} \tag{6}$$

where $j = 1, 2,..., N$.

Finally, the overall distance (or similarity) of each alternative A_j from the positive ideal solution is estimated as

$$C_j^+ = \frac{S_j^-}{S_j^* - S_j^-} \tag{7}$$

where $0 < C_j^+ < 1; j = 1, 2,..., N$

Ultimately, the best-ranked alternative is the one with the maximum C_j^+. In this case, if C_j^+ is close to 1, then the alternative A_j is considered as ideal. On the contrary, if it is closed to 0, it is considered as non-ideal.

Case study: DG system maintenance of a motor sailing cruise vessel

In any kind of FMAGDM problem, such as the selection of the best maintenance approach for the DG system of a motor sailing cruise vessel, decision makers need to take into account attributes which may be described with numerical/crisp answers, and also include answers expressed in linguistic terms. As seen through the literature review presented before as well as to the best of the authors' knowledge, there is no such application yet in the maintenance field of the maritime industry,[33,34] that is, where the novelty of this approach originates. Moreover, the suggested FMAGDM technique considers parameters such as the effectiveness of the maintenance, the crew training, the top management commitment and other attributes, which are inherently vague and thus not easily quantified. The application of FMAGDM selection of the maintenance type is initiated with the rating, aggregation and selection stage. In this respect, a brief summarised description of the formulated maintenance question along with the attributes involved and the various maintenance alternatives available is shown in Figure 1.

As is shown, the objective of the FMAGDM problem is to select the best maintenance approach for the DG system of a vessel. There are three alternatives suggested for the subject objective as shown in the 'Literature review – maintenance methodologies' section. These refer to the three different maintenance approaches, namely corrective (X_1), preventive (X_2) and predictive (X_3) maintenance. These are examined regarding eight different attributes (A_1–A_8). In more detail (Table 2),

1. Maintenance cost in case of implementation of the specific maintenance approach (A_1). In this case, maintenance cost refers to the overall cost when comparing the various maintenance alternatives;

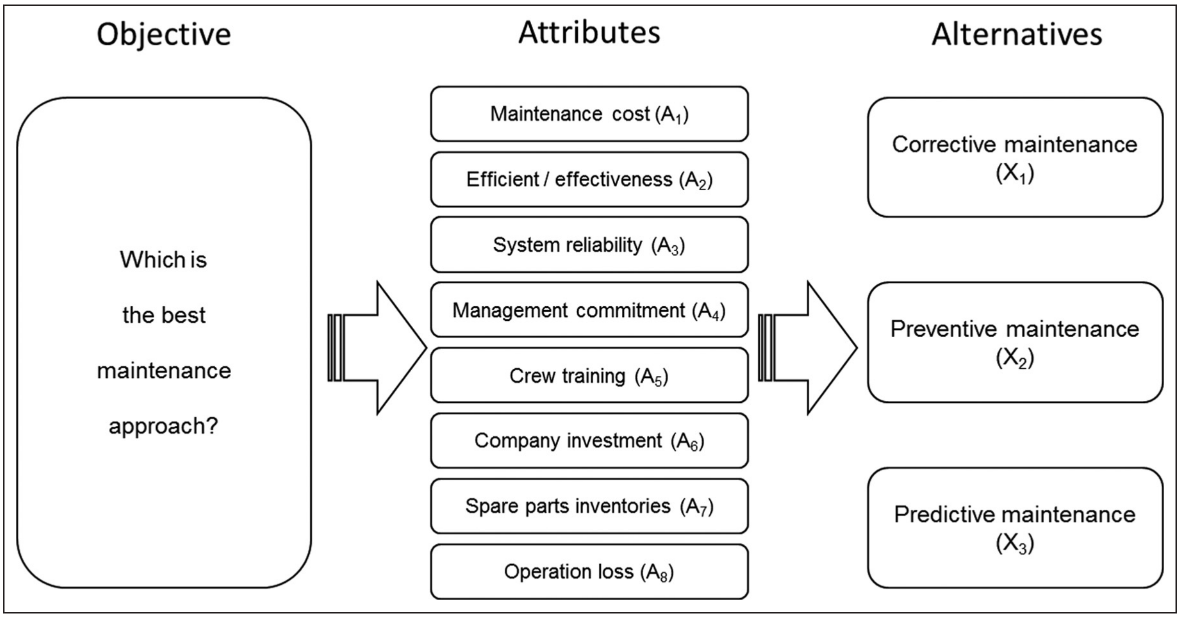

Figure 1. Fuzzy multi-attributive group decision-making study layout.

Table 2. Properties of attributes used in the case study of the ship DG system.

Attributes	Description	Type of assessment	Type of attribute	
A_1	Maintenance cost	Linguistic	Cost	Subjective
A_2	Maintenance type efficiency	Linguistic	Benefit	Subjective
A_3	System reliability	Linguistic	Benefit	Subjective
A_4	Management commitment	Linguistic	Benefit	Subjective
A_5	Crew training	Linguistic	Cost	Subjective
A_6	Company investment	Linguistic	Cost	Subjective
A_7	Spare parts inventories	Linguistic	Cost	Subjective
A_8	Minimisation operation loss	Linguistic	Benefit	Subjective

2. Maintenance-type efficiency (A_2). This attribute considers how efficient each maintenance alternative is;
3. Increase in the system reliability after implementation of the maintenance approach (A_3). The growth in the system reliability is taken into account with this attribute (this is related to the effectiveness of the attribute);
4. Top management commitment towards implementation of each of the maintenance types (A_4); with this attribute, the engagement of the high-level managerial team in order to support the maintenance effort;
5. Crew training cost involved in each maintenance type (A_5). This attribute highlights the potential crew training needed in order to get specialised knowledge in the use of equipment for carrying out the maintenance tasks (e.g. condition monitoring);
6. Company investment cost regarding each maintenance approach (A_6); discusses the initial company capital cost that needs to be tied-up in additional equipment in order to perform the selected maintenance approach;
7. Spare parts inventories (A_7); refers to the spare parts that need to be available beforehand in order to carry out the maintenance alternative;
8. Minimisation of the operation loss that may occur (A_8). The last attribute considers the extent of the operation loss that may occur in the case that a specific maintenance alternative/approach is selected.

In this case, all the attributes are described in linguistic terms. Furthermore, the attributes are categorised according to their contribution in the problem objective, that is, whether they have a benefit or cost impact on it. The last column of Table 2 signifies the subjective or objective nature of the attribute. In this case, all the attributes are of subjective type, meaning that all the initial rankings are provided based on the experts' subjective view. After having presented the alternatives as well as the related attributes for the FMAGDM maintenance problem, the specific steps followed in order to achieve the selection of the most appropriate maintenance type are explicitly shown in the next sections.

Table 3. Attribute and experts ranking and weighting factors.

Attributes	Relative importance		E_1		E_2		E_3		E_4	
		w	re	we_1	re	we_2	re	we_3	re	we_4
A_1	100	0.121	1	0.370	1	0.370	0.5	0.185	0.2	0.074
A_2	90	0.091	0.7	0.219	1	0.313	1	0.313	0.5	0.156
A_3	85	0.182	0.6	0.200	1	0.333	1	0.333	0.4	0.133
A_4	75	0.262	1	0.455	0.7	0.318	0.4	0.182	0.1	0.045
A_5	60	0.065	1	0.250	1	0.250	1	0.250	1	0.250
A_6	95	0.131	1	0.476	0.7	0.333	0.3	0.143	0.1	0.048
A_7	60	0.061	1	0.313	0.9	0.281	0.8	0.250	0.5	0.156
A_8	90	0.087	1	0.339	0.8	0.271	0.7	0.237	0.45	0.153

Rating stage

As described above, the rating stage of the different alternatives per attribute and expert involved in the FMAGDM problem is demonstrated in this section. Initially, each alternative is allocated a relative importance factor (*RI*) concerning the importance that each alternative conveys in the decision-making procedure. In this respect, the highest/most important attribute is given a factor of 100, while the rest of the attributes are compared with the highest one and are assigned lower weighting factors. Following the above, each attribute is assigned a separate weighting factor w_i with $0 < w_i < 1$ as mentioned in the 'methodology' section. The initial allocation of the mentioned factors is carried out by the selected group of experts, whose opinion is requested in the first place.

In terms of the group of experts participating in the FMAGDM, they originate from different levels of the maritime industry and accordingly each expert's operational experience and expertise on the subject matter of maintenance approach selection have been considered. More specifically, the experts who participate and provide the performance ratings of the maintenance solutions with regard to the specific attributes are the technical manager of a shipping company (E_1), a superintendent engineer (E_2), a 2nd engineering officer (E_3) and a 3rd engineering officer (E_4). In this case, the AHP method is employed in order to provide the assigned rating (*re*) and weighting (*we*) factors for each expert and each separate attribute and alternative (Table 3).

At this point, it is essential to describe the role and responsibilities of each of the experts involved in the presented case study in order to clarify the experts' overall importance in the subject FMAGDM process. The technical manager of a shipping company (E_1) is responsible for the overall technical supervision of a fleet of vessels as well as he retains the managerial overlook through the entire structure of the technical department of the company. He is also responsible for the budget allocation in the overall fleet of vessels that the company operates. The superintendent engineer (E_2) is accountable for a certain vessel or number of vessels with regard to their general performance as well as has some budgeting and management duties to perform. The second engineering officer (E_3) follows the chief engineer's guidelines and suggestions onboard the ship, while he or she supervises the jobs of the engineering personnel (e.g. 3rd engineer, oiler, wiper, etc.) carried out onboard the vessel. Finally, the third engineering officer (E_4) is the lower ranked of the four experts, attending the day-to-day operations of the ship, getting involved in various engineering tasks and gaining the valuable experience in order to build up his skills and knowledge.

Each one of the above experts is allocated different rating factors re_i as per the attribute they are asked to rank. The highest/most important rating factor assigned per expert E_i and attribute A_i is equal to 1, while the rest are compared and categorised according to their importance/relevance with the top weighting factor. For instance, expert E_1 (technical manager) is assigned a factor *re* equal to 1 for the fifth attribute (top management), while expert E_4 (third engineering officer) is assigned a factor *re* equal to 0.1 for the same attribute. Then these factors are aggregated per each attribute providing a weighting factor *we*.

What follows next is the representation of the experts' answers using the fuzzy linguistic expressions. In order to achieve the above, there are a number of different linguistic terms and their fuzzy weighting scales available as retrieved from Chen and Hwang.[37] In any FMAGDM process, one can employ either a combination of different scales or just a single scale to transform the linguistic terms into fuzzy numbers. For this study, Scale 3 is selected to be employed, using five different ranking categories ('very low', 'low', 'medium', 'high' and 'very high'). This is performed in order to provide the experts with adequate space for ranking (five different ranking options to select from) whereas at the same time also create a robust enough fuzzy scale category, which will not confuse the experts with additional (and in some cases unnecessary) linguistic terms. The abovementioned scale is used for all the solutions as well as across all the attributes described. Moreover, the experts' answers to a sample questionnaire are achieved in order to obtain their view on the selection of the most appropriate maintenance approach. The experts' responses are then transformed into fuzzy trapezoidal expressions which are eventually used for the aggregation process for each one of the different attributes mentioned in the previous section. Overall, the initial expression of the experts' opinion together with the respective standardised fuzzy numbers for each different alternative and attribute is summarised in Table 4.

Aggregation stage

In terms of the aggregation stage, the experts' ratings are collectively used for each attribute and alternative. The standardised trapezoidal fuzzy numbers are initially used in order to estimate the degree of agreement (or similarity function) *S*. Following the above, the agreement matrix (*AM*) is created as well as the average degree of agreement (*AA*) for each attribute. As described in the previous sections of this article, the relative degree of agreement (*RA*) and the consensus degree coefficient (*CC*) are calculated next. The facilitator's influence in the initial ranking of experts is also considered taking into account the β factor ($0 < \beta < 1$), initially set as 0.5 (in this case the facilitator's influence is neither low nor high). Finalising the aggregation stage, the trapezoidal fuzzy number aggregation result (*R*) is also calculated. Moreover, Table 5 shows the summarised results for all attributes alternatives and experts.

As explained above, the aggregation stage provides the necessary input for the following stage of the FMAGDM process, that is, the selection stage.

Selection stage

The selection stage is the final stage for carrying out the FMAGDM process. It consists of two separate steps. The first one considers the defuzzification of the aggregated trapezoidal fuzzy values of the matrices developed in the aggregation step and summarised in Table 6. The second step assists in the ranking the different alternatives after the defuzzification has taken place using the TOPSIS ranking method.

In the second step, the ranking of the different alternatives after the defuzzification phase is shown. In this respect, the TOPSIS method is applied in order to obtain the overall rating of the three suggested alternatives (corrective, preventive and predictive maintenance type, respectively). As explained above, the TOPSIS method is based on the initial identification of an ideal positive and negative solution and its comparison with the various suggested alternatives. The ideal positive solution derives from the best values of each attribute, while the negative one originates from the worst values of each attribute. In this respect, the positive and negative ideal solutions for each attribute and alternatives for the suggested maintenance decision-making selection are shown in Table 7.

After having set the ideal positive and negative solutions, the distance of each one of the suggested maintenance alternatives from them (S_i^+ and S_i^-, respectively) is calculated together with the final ranking C_i^+ of each alternative (Table 8).

As can be seen, alternative X_2 (preventive maintenance option) is the most favourable one in terms of being the furthest from the ideal negative solution and concurrently the closest to the ideal positive solution, while its overall C_i^+ ranking is the highest of all three alternatives. On the other hand, the predictive maintenance approach (X_3) of the DG system of the motor sailing cruise ship is ranked in the second place overall, although very close to the first alternative X_2. The latter observation denotes that predictive maintenance has gained momentum over the last few years, clearly approaching a state at which it will be preferred type of maintenance to be implemented in the next few years as the overall mind-set of the maritime industry is changing, being able to see the obvious benefits of applying predictive maintenance in the long term. Moreover, the corrective maintenance approach (X_1) is clearly ranked as the third preferred option, showing that ship operators have started steering away from this type of maintenance and moving to a predictive approach. The above results are clearly evident especially in the case of cruise ships, in which unexpected machinery system breakdowns lead not only to operational loss and additional repair expenditure but also and most importantly to depraved ship operator reputation.

Sensitivity analysis

Moreover, in order to observe the facilitator' influence in the FMAGDM process, a sensitivity analysis is performed regarding the β values. It is reminded that the β values reflect the facilitator's influence in the entire FMAGDM process. A β value of 0 denotes that there is no influence in the process, while a β value of 1 denotes that the facilitator's choice on the initial weighting factors attributed to the experts is of major importance. In this respect, the range of the β values together with the ranking results for the three suggested alternatives is shown in Figure 2.

As can be seen, the overall ranking of the decision-making approach does not change as the β values increase from 0 to 1. More specifically, corrective maintenance (X1) is still considered as the least favourable option compared to preventive (X2) and predictive (X3) ones. Moreover, although the predictive maintenance approach is ranked slightly higher than the preventive one for the lower β values (0–0.3), preventive maintenance is the most preferred one for the rest of the β values. This shows that the facilitator's influence in the entire process is of some degree, although demonstrating that the group of experts consider that the maritime maintenance regime should clearly steer away from the predominant corrective maintenance approach implemented so far.

Table 4. Experts' answers and respective standardised fuzzy numbers per alternative and attribute.

		X_1				X_2				X_3			
		E_1	E_2	E_3	E_4	E_1	E_2	E_3	E_4	E_1	E_2	E_3	E_4
A_1	Experts' opinion	High	Very high	Very high	Very high	Low	Medium	Medium	Low	Medium	Low	Very low	Very low
	Standardised fuzzy number	(0.6, 0.75, 0.75, 0.9)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.1, 0.25, 0.25, 0.4)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.1, 0.25, 0.25, 0.4)	(0.3, 0.5, 0.5, 0.7)	(0.1, 0.25, 0.25, 0.4)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)
A_2	Experts' opinion	Very low	Very low	Very low	Very low	Very high	Medium	Medium	Very high	Medium	Very high	Very high	High
	Standardised fuzzy number	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0.8, 0.9, 1, 1)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.8, 0.9, 1, 1)	(0.3, 0.5, 0.5, 0.7)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.6, 0.75, 0.75, 0.9)
A_3	Experts' opinion	Very low	Very low	Very low	Very low	Very high	Low	Medium	Very high	Low	Very high	Very high	Low
	Standardised fuzzy number	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0.8, 0.9, 1, 1)	(0.1, 0.25, 0.25, 0.4)	(0.3, 0.5, 0.5, 0.7)	(0.8, 0.9, 1, 1)	(0.1, 0.25, 0.25, 0.4)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.1, 0.25, 0.25, 0.4)
A_4	Experts' opinion	Very high	Very low	Very low	Low	High	Medium	Medium	High	Very low	Very high	Very high	Very high
	Standardised fuzzy number	(0.8, 0.9, 1, 1)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0.1, 0.25, 0.25, 0.4)	(0.6, 0.75, 0.75, 0.9)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.6, 0.75, 0.75, 0.9)	(0, 0, 0.1, 0.2)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)
A_5	Experts' opinion	High	Very low	Medium	Medium	Medium	Medium	High	Medium	Very high	Very high	Very high	Very high
	Standardised fuzzy number	(0.6, 0.75, 0.75, 0.9)	(0, 0, 0.1, 0.2)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.6, 0.75, 0.75, 0.9)	(0.3, 0.5, 0.5, 0.7)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)
A_6	Experts' opinion	Medium	Very low	Very low	Low	Medium	Medium	Medium	Medium	High	Very high	Very high	Very high
	Standardised fuzzy number	(0.3, 0.5, 0.5, 0.7)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0.1, 0.25, 0.25, 0.4)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.6, 0.75, 0.75, 0.9)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)
A_7	Experts' opinion	Medium	High	High	Very high	Very high	Medium	Medium	Medium	Low	Very low	Low	Low
	Standardised fuzzy number	(0.3, 0.5, 0.5, 0.7)	(0.6, 0.75, 0.75, 0.9)	(0.6, 0.75, 0.75, 0.9)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.1, 0.25, 0.25, 0.4)	(0, 0, 0.1, 0.2)	(0.1, 0.25, 0.25, 0.4)	(0.1, 0.25, 0.25, 0.4)
A_8	Experts' opinion	Very low	Very low	Low	Very low	Very high	Medium	Medium	High	Medium	Very high	Very high	Very high
	Standardised fuzzy number	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0.1, 0.25, 0.25, 0.4)	(0, 0, 0.1, 0.2)	(0.8, 0.9, 1, 1)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.6, 0.75, 0.75, 0.9)	(0.3, 0.5, 0.5, 0.7)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)

Table 5. Final aggregation matrix for experts E_1–E_4.

	X_1	X_2	X_3
A_1	(0.74, 0.86, 0.93, 0.97)	(0.21, 0.38, 0.38, 0.56)	(0.12, 0.22, 0.26, 0.41)
A_2	(0.00, 0.00, 0.10, 0.20)	(0.52, 0.68, 0.72, 0.83)	(0.65, 0.78, 0.84, 0.91)
A_3	(0.00, 0.00, 0.10, 0.20)	(0.46, 0.61, 0.65, 0.75)	(0.51, 0.63, 0.69, 0.75)
A_4	(0.19, 0.24, 0.32, 0.41)	(0.45, 0.62, 0.62, 0.80)	(0.64, 0.73, 0.83, 0.84)
A_5	(0.31, 0.45, 0.47, 0.64)	(0.37, 0.56, 0.56, 0.75)	(0.80, 0.90, 1.00, 1.00)
A_6	(0.12, 0.21, 0.26, 0.40)	(0.30, 0.50, 0.50, 0.70)	(0.73, 0.85, 0.91, 0.96)
A_7	(0.56, 0.71, 0.73, 0.87)	(0.42, 0.60, 0.62, 0.77)	(0.07, 0.19, 0.21, 0.35)
A_8	(0.02, 0.06, 0.13, 0.25)	(0.50, 0.66, 0.69, 0.83)	(0.67, 0.80, 0.87, 0.92)

Table 6. Defuzzified aggregated values, normalised and weighted normalised ratings for experts E_1–E_4.

		Corrective (X_1)	Preventive (X_2)	Predictive (X_3)
A_1	Defuzzified aggregated values (total score)	0.8479	0.3996	0.2796
	Normalised ratings	0.8668	0.40857	0.28586
	Weighted normalised ratings	0.10507	0.04952	0.03465
A_2	Defuzzified aggregated values (total score)	0.0909	0.6655	0.7717
	Normalised ratings	0.0889	0.65049	0.75430
	Weighted normalised ratings	0.00808	0.05914	0.06857
A_3	Defuzzified aggregated values (total score)	0.0909	0.6069	0.6336
	Normalised ratings	0.1031	0.68803	0.71832
	Weighted normalised ratings	0.01874	0.12510	0.13060
A_4	Defuzzified aggregated values (total score)	0.3031	0.6011	0.7501
	Normalised ratings	0.3007	0.59643	0.74422
	Weighted normalised ratings	0.07873	0.15616	0.19485
A_5	Defuzzified aggregated values (total score)	0.4711	0.5488	0.9091
	Normalised ratings	0.4055	0.47244	0.78255
	Weighted normalised ratings	0.02654	0.03092	0.05122
A_6	Defuzzified aggregated values (total score)	0.2724	0.5000	0.8374
	Normalised ratings	0.2690	0.49375	0.82695
	Weighted normalised ratings	0.03522	0.06464	0.10826
A_7	Defuzzified aggregated values (total score)	0.6910	0.5913	0.2375
	Normalised ratings	0.7351	0.62909	0.25261
	Weighted normalised ratings	0.04455	0.03813	0.01531
A_8	Defuzzified aggregated values (total score)	0.1388	0.6495	0.7913
	Normalised ratings	0.1343	0.62867	0.76598
	Weighted normalised ratings	0.01172	0.05487	0.06685

Table 7. Positive and negative ideal solutions for the suggested alternatives.

Attributes	Positive ideal solution	Negative ideal solution
A_1	0.0346	0.1051
A_2	0.0686	0.0081
A_3	0.1306	0.0187
A_4	0.1949	0.0787
A_5	0.0265	0.0512
A_6	0.0352	0.1083
A_7	0.0153	0.0446
A_8	0.0668	0.0117

Conclusion

In this article, an existing FMAGDM approach based on the employment of FST and AHP was presented. This approach has been used as part of the novel RCBM framework. In this respect, a thorough review on the various maintenance methodologies was performed highlighting the advantages, shortcomings and gaps identified in the existing maintenance regime. Furthermore, a case study of the selection of the best maintenance method for the DG system of a motor sailing cruise vessel was developed employing attributes such as the actual cost of the maintenance approach; its degree of efficiency as well as the increment in the system's reliability was employed. Additionally, attributes including the top management commitment, company investment, crew training cost, the cost of spare parts inventories and the reduction of the operational loss were also considered. AHP was also implemented in order to initially assist with the use of the attribute weighting factors w when considering the multi-attributive decision-making process. All the above attributes were examined when implementing three different maintenance approaches, namely corrective, preventive and predictive ones. Using the three distinctive stages of rating, aggregation and selection, FMAGDM enabled the group of decision makers to

Table 8. Distance (separation) of alternatives from positive and negative ideal solutions.

	X_1	X_2	X_3
S_i^+	0.196	0.058	0.077
S_i^-	0.077	0.165	0.196
C_i^+	0.282	0.739	0.718
Final ranking	3	1	2

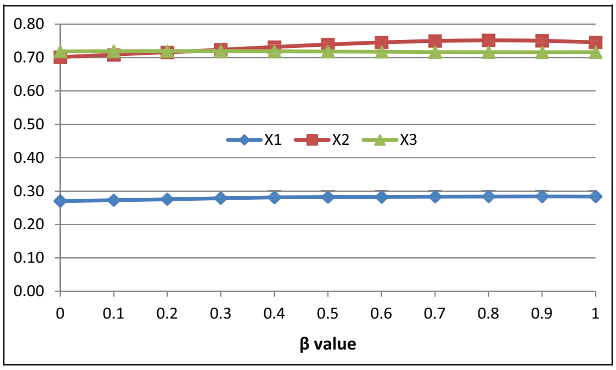

Figure 2. Graph showing the sensitivity analysis regarding different β values.

establish the best maintenance approach, that is, the preventive one, which was closely followed by predictive maintenance showing the change of attitude in the use of maintenance in the maritime industry.

Considering the above, the present study showed that decision-making can be improved by combining the benefits of FST and AHP in order to avoid vagueness of information related to the mentioned maintenance objective. Linguistic terms can be employed, rated, aggregated and ranked in order to enhance the description of the fuzzy nature of some of the attributes in question. The methodological framework presented herein also demonstrated that complex maintenance problems in the maritime industry could be addressed successfully, enabling the decision makers to make timely cost-effective decisions.

Moreover, a further enhancement of the suggested FMAGDM process would include the development of a larger group of experts with supplementary personnel from both the onshore (e.g. operation's manager) and onboard (e.g. chief engineer, cadets) environment. Crisp values for some of the attributes may also be used (e.g. cost elements for crew training, initial company investment, cost of spare parts). In the same manner, additional alternatives can be included in order to enhance the novel methodology presented herein by introducing different types of preventive (e.g. general overhauling and single repair) and predictive (e.g. continuous and interval condition monitoring) maintenance.

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References

1. Saaty TL. *The analytic hierarchy process*. New York: McGraw-Hill, 1980.
2. Ding JF, Tseng WJ and Hsu FT. An evaluation of key risk factors affecting shipping market operations across the Taiwan Strait for liner carriers. *Proc IMechE, Part M: J Engineering for the Maritime Environment* 2014; 228(3): 302–311.
3. Gaonkar RSP, Xie M and Majumdar I. Reference ship selection for the on-time performance benchmarking of ships. *Proc IMechE, Part M: J Engineering for the Maritime Environment* 2013; 227(1): 39–50.
4. Riahi R, Li K, Robertson I, et al. A proposed decision-making model for evaluating a container's security score. *Proc IMechE, Part M: J Engineering for the Maritime Environment* 2014; 228(1): 81–104.
5. Gaonkar RSP, Xie M, Habibullah MS, et al. Comparative studies of multi-criteria decision making with application to condition monitoring of a ship turbine. *Proc IMechE, Part M: J Engineering for the Maritime Environment* 2011; 225(2): 149–160.
6. Boulougouris EK, Papanikolaou AD and Pavlou A. Energy efficiency parametric design tool in the framework of holistic ship design optimization. *Proc IMechE, Part M: J Engineering for the Maritime Environment* 2011; 225(3): 242–260.
7. Theotokatos G and Livanos G. Techno-economical analysis of single pressure exhaust gas waste heat recovery systems in marine propulsion plants. *Proc IMechE, Part M: J Engineering for the Maritime Environment* 2013; 227(2): 83–97.
8. BS/ISO 3811:1993. Glossary of terms used in terotechnology (Common BSI/ISO standard, London).
9. UK Ministry of Defence (UK MoD) – Defence Standard 00-45:2006. Using reliability centred maintenance to manage engineering failures – part 3. Guidance on the application of reliability centred maintenance, London.
10. Blanchard BS. *Logistics engineering and management*. Englewood Cliffs, NJ: Prentice Hall, 1992.
11. Kelly A. *Maintenance planning and control*. Cambridge: Butterworth & Co., 1984.
12. Rodriguez V and Woodhouse J. *PDVSA: an implementation story of risk-based asset management*. PDVSA & The Woodhouse Partnership Ltd, 2003. UK: Hampshire
13. BSI – PAS 55-2:2008. PAS 55-2-Asset management part 2: guidelines for the application of PAS 55-1, London.
14. ISO 55000:2013. ISO 55000 standard for asset management, http://www.assetmanagementstandards.com/ (accessed 7 December 2013).
15. Nakajima S. *Introduction to total productive maintenance*. Cambridge, MA: Productivity Press Inc., 1988.
16. Ahuja IPS and Khamba JS. Total productive maintenance: literature review and directions. *Int J Qual Reliab Manag* 2008; 25(7): 709–756.
17. Shamsuddin A, Masjuki HH and Zahari T. TPM can go beyond maintenance: excerpt from a case implementation. *J Qual Mainten Eng* 2005; 11(1): 19–42.

18. Bohoris GA, Vamvalis C, Tracey W, et al. TPM implementation in Land-Rover with the assistance of a CMMS. *J Qual Mainten Eng* 1995; 1(4): 3–16.
19. Cooke FL. Implementing TPM in plant maintenance: some organisational barriers. *Int J Qual Reliab Manag* 2000; 17(9): 1003–1016.
20. Chan FTS, Lau HCW, Ip RWL, et al. Implementation of total productive maintenance: a case study. *Int J Prod Econ* 2005; 95: 71–94.
21. Alsyouf I. Maintenance practices in Swedish industries: survey results. *Int J Prod Econ* 2009; 121: 212–223.
22. Arca J and Prado JC. Personnel participation as a key factor for success in maintenance program implementation: a case study. *Int J Prod Perform Manag* 2008; 57(3): 247–258.
23. Khan FI, Sadiq R and Haddara MM. Risk-based inspection and maintenance (RBIM): multi attribute decision making with aggregative risk analysis. *Process Saf Environ* 2004; 82(B6): 398–411.
24. Patel RJ. Risk based inspection. In: *3rd MENDT – middle east non-destructive testing conference & exhibition*, Manama, Bahrain 27–30 November 2005.
25. Tsang AHC, Yeung WK, Jardine AKS, et al. Data management for CBM optimization. *J Qual Mainten Eng* 2006; 12(1): 37–51.
26. Ross JM. Condition based maintenance – a tool for improving productivity in shipyards. *J Ship Prod* 2002; 18(3): 175–184.
27. ATA. *Maintenance evaluation and programme development: 737 maintenance steering group handbook (MSG 1)*. Washington, DC: ATA, 1968.
28. Moubray J. *Reliability-centred maintenance II*. Oxford: Butterworth-Heinemann Ltd, 1991.
29. Fonseca DJ and Knapp GM. An expert system for reliability centered maintenance in the chemical industry. *Expert Syst Appl* 2000; 19: 45–57.
30. Gabbar HA, Yamashita H, Suzuki K, et al. Computer-aided RCM-based plant maintenance management system. *Robot Cim: Int Manuf* 2003; 19: 449–458.
31. Rausand M and Vatn J. Reliability centred maintenance. In: Kobbacy KAH and Murthy DNP (eds) *Complex system maintenance handbook*. London: Springer-Verlag, 2008, pp.79–108.
32. Lazakis I. *Establishing an innovative and integrated reliability and criticality based maintenance strategy for the maritime industry*. PhD Thesis, Department of Naval Architecture and Marine Engineering (NAME), University of Strathclyde, Glasgow, 2011.
33. Lazakis I, Turan O, Aksu S, et al. Increasing ship operational reliability through the implementation of a holistic maintenance management strategy. *J Ships Offshore Structure* 2010; 5(4): 337–357.
34. Turan O, Lazakis I, Judah S, et al. Investigating the reliability and criticality of the maintenance characteristics of a diving support vessel. *Qual Reliab Eng Int* 2011; 27(7): 931–946.
35. Zadeh LA. Fuzzy sets. *Inform Control* 1965; 8: 338–353.
36. Zimmermann HJ. *Fuzzy set theory and its applications*. 2nd ed. Boston, MA: Kluwer Academic Publishers, 1991.
37. Chen SJ and Hwang CL. *Fuzzy multiple attribute decision making: methods and applications*. New York: Springer-Verlag, 1992.
38. Ross TJ. *Fuzzy logic with engineering applications*. 3rd ed. Hoboken, NJ: Wiley, 2010.
39. Wang L, Chua J and Wu J. Selection of optimum maintenance strategies based on a fuzzy analytic hierarchy process. *Int J Prod Econ* 2007; 107: 151–163.
40. Yuniarto MN and Labib AW. Fuzzy adaptive preventive maintenance in a manufacturing control system: a step towards self-maintenance. *Int J Prod Res* 2006; 44(1): 159–180.
41. Carasco EF, Rodrıä guez J, Puñal A, et al. Rule-based diagnosis and supervision of a pilot-scale wastewater treatment plant using fuzzy logic techniques. *Expert Syst Appl* 2002; 22: 11–20.
42. Riahi H, Bonsall S, Jenkinson ID, et al. A proposed fuzzy evidential reasoning (FER) model for measuring seafarers' reliability. In: *Proceedings of the international conference on human performance at sea (HPAS)*, Glasgow, 16–18 June 2011, pp.497–508. UK: University of Strathclyde.
43. Ölçer Aİ and Odabasi AY. A new fuzzy multiple attributive group decision making methodology and its application to propulsion/manoeuvring system selection problem. *Eur J Oper Res* 2005; 166(1): 93–114.
44. Nwaoha TC, Yang Z, Wang J, et al. A new fuzzy evidential reasoning method for risk analysis and control of a liquefied natural gas carrier system. *Proc IMechE, Part M: J Engineering for the Maritime Environment* 2011; 225: 206–225.
45. Labib AW, Williams GB and O'Connor RF. An intelligent maintenance model (System): an application of the analytic hierarchy process and a fuzzy logic rule-based controller. *J Oper Res Soc* 1998; 49(7): 745–757.
46. Mansor MR, Sapuan SM, Zainudin ES, et al. Hybrid natural and glass fibers reinforced polymer composites material selection using analytical hierarchy process for automotive brake lever design. *Mater Design* 2013; 51: 484–492, http://dx.doi.org/10.1016/j.matdes.2013.04.072
47. An M, Chen Y and Baker CJ. A fuzzy reasoning and fuzzy-analytical hierarchy process based approach to the process of railway risk information: a railway risk management system. *Inform Sciences* 2011; 181: 3946–3966.
48. Arslan O and Turan O. Analytical investigation of marine casualties at the strait of Istanbul with SWOT-AHP method. *Marit Pol Manag* 2009; 36(2): 131–146.
49. Song W, Ming X, Wu Z, et al. A rough TOPSIS approach for failure mode and effects analysis in uncertain environments. *Qual Reliab Eng Int* 2013; 4: 473–486.
50. Braglia M, Frosolini M and Montanari R. Fuzzy TOPSIS approach for failure mode, effects and criticality analysis. *Qual Reliab Eng Int* 2003; 19: 425–443.