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Multi-Criteria based Selection of Ship-Based Ballast Water Treatment Technologies

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Abstract

The reality of selecting an acceptable ballast water treatment technology is a daunting task for end-users, due to availability of numerous treatment options and their efficacy in given ship-types and ballast voyages. Six treatment systems have been selected from the two generic treatment technology groups (physical solid liquid separation and disinfection), and are considered as the decision making alternatives in the proposed model. The proposed model involves the application of the Technique for Order Performance by Similarity to the Ideal Solution (TOPSIS), in the decision-making analysis. The TOPSIS technique has been applied to obtain the performance ratings of the decision alternatives using linguistic terms parameterised with triangular fuzzy numbers. A sensitivity study is also conducted to identify the effects of changes in input data, and test the suitability of the developed model in decision-making analysis of ballast water treatment systems.

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1. Introduction

Regulations D2 and D4 of the IMO International Convention for the Control and Management of Ships' Ballast Water and Sediments Ballast Water (2004), stipulate that all ships under construction in or after 2009 and having a ballast capacity between 1,500 and 5,000m^3, must have ballast water treatment systems fitted to and used on-board with effect from January 1, 2009.[1] Compliance to such IMO Regulations has propelled the development of numerous ballast water treatment technologies. The selection of a particular treatment system for a designated vessel or voyage route will have to be pre-determined by technical (safety of crew, ship and cargo), cost (production and running) and environmental (sustainability of the marine eco-systems) variables.

Evaluating these variables may not be straightforward due to inherent uncertainties and inadequacy of historical data. The choice of an appropriate ballast water treatment system can therefore, be a daunting task for both ship-owners and managers. Port states and/or regional regulatory authorities are also subject to decision-making problems, as they are expected to strike a balance between the sustenance of a pollution-free maritime environment, and the promotion of maritime trade of their countries/regions.

A novel model is developed in this paper to deal with multiple criteria decision-making (MCDM) problems associated with the analysis and selection of ballast water treatment systems, under a subjective group decision framework. A group decision-making problem arises when there are two or more individuals who, characterized by their perceptions, attitudes, motivations, and personalities, recognize the existence of a common problem and attempt to reach a collective decision.[2] In the developed model, fuzzy sets theory (FST), Analytic Hierarchy Process (AHP) and the Technique for Order Performance by Similarity to the Ideal Solution (TOPSIS) are used for the analysis of decision-making variables in a holistic way. AHP is incorporated into the model to determine the importance weights of the decision criteria, while the TOPSIS technique is used to obtain the performance ratings of decision alternatives.

The rest of the paper is structured as described in the next sentences. Following a brief literature review of decision-making analysis, a model for selecting the best ballast water treatment system is presented. Then the proposed model is demonstrated using a test case, with a sensitivity analysis to validate the findings, before the conclusion at the end.

2. Background to the research

Bellman & Zadeh (1970)[3] surveyed decision-making problems using fuzzy sets, and initiated a Fuzzy Multiple Criteria Decision Making (FMCDM) methodology to resolve the lack of precision, in assigning importance weights of criteria and the ratings of alternatives.[4,5] FMCDM has been applied in broad fields that include: the selection of strategic alliances partners for liner shipping;[6] safety assessment;[7] tool steel material selection;[8] assessment of climate change;[9] distribution centre location selection;[10] selection of a maintenance strategy for marine and offshore machinery operations;[11] and airline service quality evaluation.[12]

A Multiple Criteria Decision Making (MCDM) problem can be defined as follows:

Let $A = \{A_i$ for $i = 1, 2, \ldots, m\}$ be a (finite) set of decision alternatives and $G = \{g_i$ for $j = 1,2,3,\ldots, n\}$ be a (finite) set of goals according to which the desirability of an action is judged. Determine the optimal alternative with the highest degree of desirability with respect to all relevant goals g_i.[13]

Linguistic term sets used for describing each fundamental parameter are decided according to the situation of the case of interest.[14] However, some literature[15,16,17] shows that the number of linguistic terms ranging between four and seven labels, is commonly acceptable to represent risk factors in engineering risk analysis. In this study, five linguistic terms have been used to describe the evaluation criteria.

TOPSIS is a linear weighting technique which was first proposed in its crisp version by Chen and Hwang (1992)[18] with reference to Hwang and Yoon (1981)'s work.[19] The technique was developed based on the concept that the chosen alternative should have the shortest distance from the positive ideal reference point (PIRP), and the farthest distance from the negative ideal reference point (NIRP).[20] Assume that each attribute in the decision matrix takes either a monotonically increasing or monotonically decreasing utility; it will be easier to locate the positive ideal solution, which is a combination of all the best attribute values attainable, while the negative ideal solution is a combination of all the worse attribute values attainable.[21]

TOPSIS has been proved to be one of the best methods in addressing the rank reversal issue; that is, the change in the ranking of alternatives when a non-optimal alternative is introduced.[19] Moreover, it has been proved to be insensitive to the number of alternatives and has its worst performance only in case of a very limited number of criteria. TOPSIS has been applied in varied and robust fields such as: evaluation and selection of initial training aircraft[5]; outsourcing of third party logistics service providers;[19] materials selection;[22] evaluation of competitive companies;[23] and the assessment of service quality in the airline industry.[12]

Fuzzy-TOPSIS is a fuzzy extension of TOPSIS to efficiently handle the fuzziness of data to be applied in the decision-making process. A fuzzy approach to TOPSIS is often advantageous, because it assigns the relative importance of attributes using fuzzy numbers instead of precise numbers. Linguistic preferences can easily be converted to fuzzy numbers and TOPSIS allows the use of these fuzzy numbers in the calculation.

In order to apply a fuzzy TOPSIS to a MCDM problem, selection criteria have to be monotonic. Monotonic criteria could be classified either as benefits (B) or as costs (C). In fuzzy TOPSIS, the cost criteria are defined as the most desirable candidates scoring at the lowest, while the benefit criteria are described as the most desirable candidate scoring at the highest. Other advantages of the Fuzzy-TOPSIS technique include the fact that:[19,23,24]

1. The logic is rational and understandable.
2. Computation processes are straightforward.
3. The concept permits the pursuit of best alternatives for each criterion depicted in a simple mathematical form.
4. It allows the straight linguistic definition of weights and ratings under each criterion, without the need of cumbersome pairwise comparisons and the risk of inconsistencies.
5. The obtained weights of evaluation criteria are incorporated into the comparison procedures.

Given the stochastic nature of species assemblages, current inadequacy of historical data on non-indigenous invasive species (NIS) origin and dispersal mechanisms within the bio-geographical regions of the world, the fuzzy TOPSIS model has been proposed as an alternative technique for use in the analysis of ballast water treatment decision options. While the uncertainty issue is tackled by means of fuzzy logic, the application of TOPSIS makes it possible to investigate the distances of each decision option from the PIRP and NIRP. Moreover, the way linguistic ratings and weights are given is very straightforward.

The triangular fuzzy numbers are applied in the Fuzzy-TOPSIS used in this study. This is because it is intuitively easy for the decision-makers to use and calculate.[25] Secondly, modelling using triangular fuzzy numbers has proven to be an effective way for the formulation of the decision problem, where the information is subjective and imprecise.[25]

Let $\tilde{A}$ and $\tilde{B}$ be two triangular fuzzy numbers denoted by the triplet (a_1, a_2, a_3) and (b_1, b_2, b_3) respectively. Then the basic fuzzy arithmetical operations on these two fuzzy numbers are defined as:[26]

$$\tilde{A}\ (+)\tilde{B} = (a_1,\ a_2, a_3)\ (+)\ (b_1,\ b_2, b_3,) = (a_1{+}b_1, a_2{+}b_2, a_3{+}b_3) \tag{1}$$

$$\tilde{A}\ (-)\tilde{B} = (a_1,\ a_2, a_3,)\ (-)\ (b_1,\ b_2, b_3,) = (a_1{-}b_3,\ a_2{-}b_2, a_3{-}\ b_1) \tag{2}$$

$$\tilde{A}\ (\mathrm{x})\tilde{B} = (a_1,\ a_2, a_3,)\ (\times)\ (b_1,\ b_2, b_3,) = (a_1 b_1,\ a_2 b_2,\ a_3 b_3) \tag{3}$$

$$\tilde{A}\ (\div)\tilde{B} = (a_1,\ a_2, a_3,)\ (\div)\ (b_1,\ b_2, b_3,) = \left(\frac{a_1}{b_3}, \frac{a_2}{b_2}, \frac{a_3}{b_1}\right) \tag{4}$$

The distance between fuzzy numbers $\tilde{A}$ and $\tilde{B}$ can be measured using the vertex method[27] and calculated using the following equation:

$$d(\tilde{A}, \tilde{B}) = \sqrt{\frac{1}{3}[(a_1 - b_1)^2 + \quad (a_2 - b_2)^2 + \quad (a_3 - b_3)^2]} \tag{5}$$

3. A Proposed Model for Selecting the best Ballast Water Treatment System

The proposed model and hierarchical structure describing the decision-making process of selecting the best ballast water treatment system is graphically illustrated in Fig. 1. The first stage is the identification of decision-making alternatives for ship-based ballast water treatment. The decision alternatives are literature-based and have been derived from the IMO Ballast Water Convention 2004 and the Lloyds Report 2007.[1,28] The evaluation process is conducted by decision analysts based on their subjective knowledge and judgment.

The second stage in the model is the identification of the evaluation criteria for the identified prototype treatment technologies. In the third stage, AHP is applied to obtain the importance weights of the evaluation criteria. In the fourth stage, Fuzzy-TOPSIS is applied to obtain the performance ratings of the various decision alternatives.

3.1 Identification of Evaluation Criteria

Five evaluation criteria have been identified for the evaluation of the decision alternatives. The criteria are based on the IMO guidelines for the development of prototype treatment technologies for on-board ballast water treatment.[28] They include:

1. Saving in Cost (savings in expense of treatment equipment and operations).
2. Practicability (ease of operating treatment equipment and interference with normal ship operations, as well as impact on the structural integrity of the ship).
3. Safety (of crew, ship and cargo).
4. Environmental Acceptability (not causing more or greater environmental impact than it solves).

5. Biological Effectiveness (efficacy or effectiveness of removing or otherwise rendering inactive harmful non-indigenous invasive species (NIS) in ballast water).

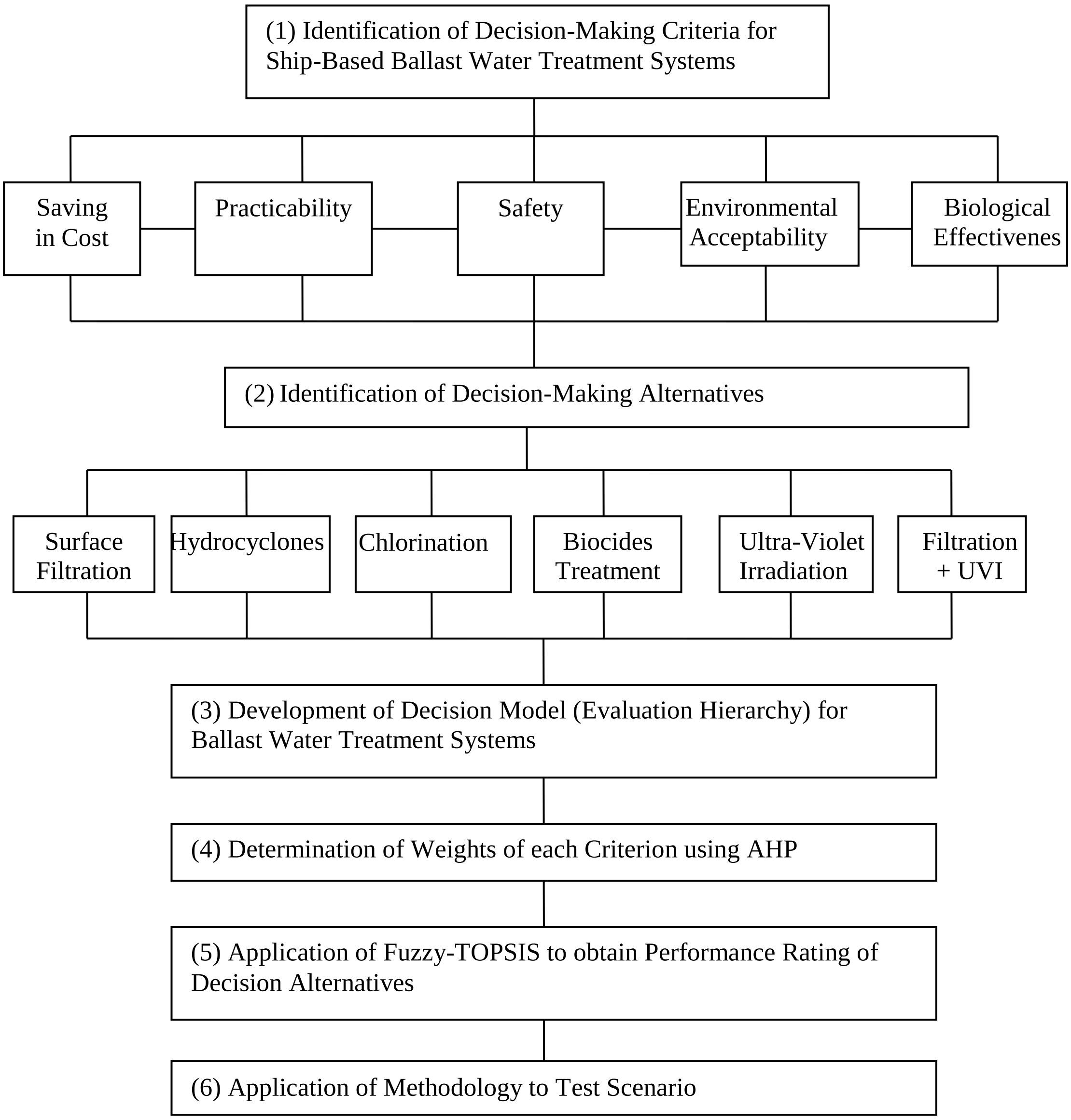

Figure 1 Hierarchical Model of Decision Making

3.2 Identification of Decision-Making Alternatives

Six decision-making alternatives have been identified and applied in this model, including surface filtration, hydro-cyclones, chlorination, biocides treatment, ultra-violet irradiation, and the combination of filtration and ultra-violet irradiation. The treatment systems have been selected from the generic ballast water treatment technologies (physical solid-liquid separation (primary treatment) and disinfection (secondary treatment)) recommended by the IMO for the global maritime industry.[1]

3.3 Determination of Importance Weights of Decision Alternatives Using AHP

The next step in the methodology is the determination of importance weights of the five criteria described above, using the AHP approach involving a panel of domain experts. A consistency check is conducted to ensure that the pair-wise comparisons in the AHP are within the acceptable consistency. Experts may be revisited for their judgements, if the consistency of pair-wise comparisons is outside the required limit.

3.4 Application of Fuzzy-TOPSIS Approach to Obtain Performance Rating of Decision Alternatives

In this assessment process, all the variables are fuzzy variables represented by triangular fuzzy numbers. The process is conducted as follows.

3.4.1 Construction of Fuzzy Decision Matrix

A decision matrix is an (m×n) matrix in which *element*$_{ij}$ indicates the performance of alternative A_i when it is evaluated in terms of decision criterion C_j (i = 1,2,3, ..., m; j = 1,2,3, …., n).[7] From this definition, it is implied that an MCDM problem with a given decision matrix is in essence a problem for a set of known alternatives and a set of known criteria.[7]

Given m alternatives, n criteria and s decision analysts, a typical fuzzy MCDM problem can be represented using the following matrix:[5,19]

$$R_k = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \left[\begin{array}{cccc} \tilde{r}_{11} & \tilde{r}_{12} & \cdots & \tilde{r}_{1n} \\ \tilde{r}_{21} & \tilde{r}_{22} & \cdots & \tilde{r}_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \tilde{r}_{m1} & \tilde{r}_{m2} & \cdots & \tilde{r}_{mn} \end{array}\right) \end{array} \quad (6)$$

where, A_1,A_2, ….,$A_m$represent the decision alternatives; C_1, C_2, …., C_n represent the evaluation criteria, and $\tilde{r}_{ij}$ represents the rating of the alternative A_i when examined in terms of criterion C_j evaluated by the s decision analysts.

3.4.2 Normalisation of Fuzzy Decision Matrix

The fuzzy data obtained in the decision matrix are normalised in order to eliminate the units of criteria scores, so that numerical comparisons associated with MCDM problems can be brought to the same universe of discourse. Normalisation has two main aims: for the comparison of heterogeneous criteria, and to ensure that all triangular fuzzy numbers range within the interval between 0 and 1.[5] The normalised fuzzy-decision matrix is conducted using Equations 7 and 8 as follows:

If $\tilde{R}$ denotes the normalised fuzzy decision matrix, then

$$\tilde{R}=\left[\tilde{r}_{ij}\right]_{mxn},\ i = 1, 2, ..., m;\ j = 1, 2, \ldots, n \quad (7)$$

$$\text{where } \tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^+}, \frac{b_{ij}}{c_j^+}, \frac{c_{ij}}{c_j^+}\right) j \in B; \qquad \tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) j \in C \quad (8)$$

$c_j^+ = \max\limits_i c_{ij}$ when $j \in B$; $a_j^- = \min\limits_i a_{ij}$ when $j \in C$.

3.4.3 Construction of Weighted Normalised Fuzzy Decision Matrix

The process involves multiplying the importance weights of the criteria by their corresponding values in the normalised fuzzy decision matrix. Considering the different importance of each criterion, the weighted normalized fuzzy-decision matrix $\tilde{V}$is constructed as:

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{m\times n} i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \quad (9)$$

$$\tilde{v}_{ij} = \tilde{R}_{ij} \times \tilde{w}_j \tag{10}$$

where $\tilde{w}_j$denotes the importance weight of criterion C_j.

3.4.4 Determination of the Fuzzy Positive Ideal Reference Point (FPIRP) and Fuzzy Negative Ideal Reference Point (FNIRP)

The FPIRP is obtained by identifying the best score in a criterion. Similarly, the worst score of a criterion is identified and recorded as the FNIRP. Against the background that all the triangular fuzzy numbers in $\tilde{V}$ are in the interval (0, 1), the FPIRP (A^+) (the benefit criterion) and FNIRP (A^-) (the cost criterion) are defined as follows[4]:

$$A^+ = (\tilde{v}_1^+, \tilde{v}_2^+, \rightleftarrows \ldots\ldots, \tilde{v}_n^+) \tag{11}$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \rightleftarrows \ldots\ldots, \tilde{v}_n^-) \tag{12}$$

where $\tilde{v}_j^+ = (1,1,1)$ and$\tilde{v}_j^- = (0,0,0)$, j =1, 2, …, n

3.4.5 Calculation of Distances of Each Alternative to FPIRP and FNIRP

The distance of each alternative (treatment system) from the FPIRP and FNIRP with respect to each criterion is calculated as follows.

$$d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^+) \tag{13}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-) \tag{14}$$

where d_i^+ denotes the distance of alternative A_i from FPIRP, $d(\tilde{v}_{ij}, \tilde{v}_j^+)$ denotes the distance measurement between $\tilde{v}_{ij}$ and $\tilde{v}_j^+$; d_i^- is the distance of alternative A_i from FNIRP, and $d(\tilde{v}_{ij}, \tilde{v}_j^-)$ denotes the distance measurement between $\tilde{v}_{ij}$ and $\tilde{v}_j^-$.

3.4.6 Obtain the Closeness Coefficient and Ranking of Alternatives

The ranking of the alternatives can be determined after the Closeness Coefficient (CC_i) associated with A_i is obtained. This allows the decision maker to choose the most rational alternative. CC_i can be calculated by:

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad i = 1, 2, \ldots., m \tag{15}$$

where CC_i is equal to 0 if and only if d_i^- = 0 or $A_i = A^-$. CC_i = 1 when d_i^+ = 0 or $A_i = A^+$. As a result, the best alternative is the one with the value of CC_i closest to 1.

4. Application of Methodology to a Test Scenario

The proposed model will be demonstrated in a decision analysis of selecting on-board ballast water treatment technologies. In this study, five qualified and experienced experts have been identified to conduct the analysis. The analysts are assigned equal ratings and the analysis will be conducted through brainstorming based on their knowledge and experience.

The weight values for the evaluation criteria are obtained as follows using the AHP approach:[29]

Saving in Cost = 0.068

Practicability = 0.171
Safety = 0.392
Environmental Acceptability = 0.237
Biological Effectiveness = 0.132

The importance weight distributions for the decision-making criteria show that the criterion “Safety” recorded the highest weight (0.392), whereas the lowest weight (0.068) is associated with the criterion “Saving in Cost”. These importance weights will be applied in the next stage of this study, to establish the fuzzy performance ratings of the evaluation criteria.

The six decision alternatives and five evaluation criteria (Table 1) will be used to develop the fuzzy decision matrix.

Table 1 TOPSIS decision alternatives and evaluation criteria

Decision alternatives		Evaluation criteria	
A_1	Surface Filtration	C_1	Saving in Cost
A_2	Hydrocyclones	C_2	Practicability
A_3	Chlorination	C_3	Safety
A_4	Biocides	C_4	Environmental Acceptability
A_5	UV Irradiation	C_5	Biological Effectiveness
A_6	Filtration + UV Irradiation		

4.1 Construction of a Fuzzy-TOPSIS Decision Matrix

The membership functions of the linguistic variables, and scales developed for the measurement of the importance of the evaluation criteria, are shown in Table 2. A Fuzzy-TOPSIS decision matrix is then constructed as shown in Table 3.

Table 2 Fuzzy-linguistic scales for measuring performance of evaluation criteria

Linguistic Variable	Corresponding Triangular Fuzzy Number
Very Poor	(0, 1, 3)
Poor	(1, 3, 5)
Average	(3, 5, 7)
Good	(5, 7, 9)
Very Good	(7, 9, 10)

Table 3 Fuzzy TOPSIS decision matrix

	C_1	C_2	C_3	C_4	C_5
A_1	5,7,9	7,9,10	5,7,9	7,9,10	5,7,9
A_2	5,7,9	5,7,9	5,7,9	7,9,10	5,7,9
A_3	3,5,7	5,7,9	5,7,9	3,5,7	5,7,9
A_4	3,5,7	5,7,9	3,5,7	1,3,5	5,7,9
A_5	5,7,9	5,7,9	3,5,7	5,7,9	5,7,9
A_6	5,7,9	7,9,10	7,9,10	7,9,10	7,9,10

4.2 Normalisation of Fuzzy Decision Matrix

The normalized fuzzy decision matrix is constructed using Equations 7 and 8. The results are shown in Table 4.

Table 4 Fuzzy TOPSIS normalized decision matrix

	C_1	C_2	C_3	C_4	C_5
A_1	0.5555, 0.7777, 1.0000	0.7000, 0.9000, 1.0000	0.5000, 0.7000, 0.9000	0.7000, 0.9000, 1.0000	0.5000, 0.7000, 0.9000
A_2	0.5555, 0.7777, 1.0000	0.5000, 0.7000, 0.9000	0.5000, 0.7000, 0.9000	0.5000, 0.7000, 0.9000	0.5000, 0.7000, 0.9000
A_3	0.3333, 0.5555, 0.7777	0.5000, 0.7000, 0.9000	0.5000, 0.7000, 0.9000	0.3000, 0.5000, 0.7000	0.5000, 0.7000, 0.9000
A_4	0.3333, 0.5555, 0.7777	0.5000, 0.7000, 0.9000	0.3000, 0.5000, 0.7000	0.1000, 0.3000, 0.5000	0.5000, 0.7000, 0.9000
A_5	0.5555, 0.7777, 1.0000	0.5000, 0.7000, 0.9000	0.3000, 0.5000, 0.7000	0.5000, 0.7000, 0.9000	0.5000, 0.7000, 0.9000
A_6	0.5555, 0.7777, 1.0000	0.7000, 0.9000, 1.0000	0.7000, 0.9000, 1.0000	0.7000, 0.9000, 1.0000	0.7000, 0.9000, 1.0000

4.3 Construction of Weighted Normalised Fuzzy-Decision Matrix

The weighted normalized decision matrix is constructed by applying Equations 9 and 10. The normalized triangular fuzzy numbers are obtained as shown in Table 5. For example, the weighted normalized fuzzy number for A_3 with respect to C_2 is obtained as follows.

$(0.500, 0.700, 0.900) \times 0.171 = (0.086, 0.120, 0.154)$

Table 5 Weighted Normalised Decision Matrix of the Six Ballast Water Treatment Systems

	C_1	C_2	C_3	C_4	C_5
A_1	0.038, 0.053, 0.068	0.119, 0.153, 0.171	0.196, 0.274, 0.352	0.165, 0.213, 0.237	0.066, 0.092, 0.118
A_2	0.038, 0.053, 0.068	0.086, 0.120, 0.154	0.196, 0.274, 0.353	0.166, 0.213, 0.237	0.066, 0.092, 0.119
A_3	0.023, 0.038, 0.053	0.086, 0.120, 0.154	0.196, 0.274, 0.353	0.071, 0.119, 0.166	0.066, 0.092, 0.119
A_4	0.023, 0.038, 0.053	0.086, 0.120, 0.154	0.118, 0.196, 0.274	0.024, 0.071, 0.119	0.066, 0.092, 0.119
A_5	0.038, 0.053, 0.068	0.086, 0.120, 0.154	0.118, 0.196, 0.274	0.119, 0.166, 0.213	0.066, 0.092, 0.119
A_6	0.038, 0.053, 0.068	0.120, 0.154, 0.171	0.274, 0.353, 0.392	0.166, 0.213, 0.237	0.092, 0.119, 0.132

4.4 Determination of the Fuzzy Positive Ideal Reference Point (FPIRP) and Fuzzy Negative Ideal Reference Point (FNIRP)

d_i^+ and d_i^- are obtained using Equations 13 and 14. For example, d_1^+ and d_1^- are obtained as follows:

$$d_1^+ = \sqrt{\frac{1}{3}[(0.0378-1)^2 + \quad (0.0539-1)^2 + \quad (0.0680-1)^2]} +$$

$$\sqrt{\frac{1}{3}[(0.1197-1)^2 + \quad (0.1539-1)^2 + \quad (0.1710-1)^2]}$$

$$+\sqrt{\frac{1}{3}[(0.1960-1)^2+\quad(0.2744-1)^2+\quad(0.3528-1)^2]}+$$

$$\sqrt{\frac{1}{3}[(0.15689-1)^2+\quad(0.2744-1)^2+\quad(0.3528-1)^2]}$$

$$+\sqrt{\frac{1}{3}[(0.0660-1)^2+\quad(0.0924-1)^2+\quad(0.1188-1)^2]}= 4.231$$

$$d_1^{-}=\sqrt{\frac{1}{3}[(0.0378-0)^2+\quad(0.0529-0)^2+\quad(0.068-0)^2]}+$$

$$\sqrt{\frac{1}{3}[(0.1197-0)^2+\quad(0.1539-0)^2+\quad(0.1710-0)^2]}$$

$$+\sqrt{\frac{1}{3}[(0.1960-0)^2+\quad(0.2744-0)^2+\quad(0.3528-0)^2]}$$

$$+\sqrt{\frac{1}{3}[(0.1659-0)^2+\quad(0.2133-0)^2+\quad(0.2370-0)^2]}$$

$$+\sqrt{\frac{1}{3}[(0.066-0)^2+\quad(0.0924-0)^2+\quad(0.1188-0)^2]} = 0.788$$

The distances of the other decision alternatives to the FRIRP and ENIRP were determined in the same way and the results are described in Table 6.

Table 6 Results of Fuzzy TOPSIS analysis

	Decision Making Criterion	d^+	d^-	Closeness Coefficient	Ranking
A_1	Surface Filtration	4.231	0.788	0.157	2
A_2	Hydrocyclones	4.299	0.724	0.144	3
A_3	Chlorination	4.362	0.663	0.132	4
A_4	Biocides	4.487	0.545	0.108	6
A_5	UV Irradiation	4.377	0.649	0.129	5
A_6	Filtration + UV Irradiation	4.142	0.870	0.174	1

4.5 Obtain Closeness Co-efficient and Ranking of Alternatives

The treatment system with a larger CC value is more desirable. The calculation of the CC value has been described below using A_1 as an example.

$d_1{}^{+}$ = 4.231 $d_1{}^{-}$ = 0.788 $CC_1 = \frac{0.788}{4.231+0.788}$= 0.157

By applying the same method, the Closeness Coefficient values of attributes A_2 - A_6 are obtained as shown in Table 6.

5. Results and Validation of Model

From the result of the Fuzzy-TOPSIS analysis (Table 6), it can be seen that the highest CC value (0.174) is associated with A_6 (Filtration + UV Irradiation). The lowest CC value (0.108) is associated with A_4 (Biocides). The result also shows that A_2 is ranked third with a CC value of 0.144. A_3 is ranked fourth having returned a CC value of 0.132, while A_5 is placed fifth in the ranking with a CC value of 0.129.

The result also shows that the CC values of the six decision alternatives are marginally separated. This suggests the degree of reasonableness and relative closeness of the systems for the treatment of ships' ballast water. Based on the output values obtained in this analysis, the ranking (in order of preference) of the six decision alternatives in descending order is: $A_6 > A_1 > A_2 > A_3 > A_5 > A_4$.

In order to validate and test the robustness of this model, a sensitivity analysis is conducted. The analysis is necessary in order to test the suitability and sensitivity of the model for decision analysis of prototype ballast water treatment technologies (as decision alternatives). The analysis is conducted under eight conditions as tabulated in Table 7.

Table 7 Conditions for changing output values by percentages

Condition	Percentage
1	Increase d^+ by 5%
2	Increase d^- by 5%
3	Decrease d^+ by 5%
4	Decrease d^- by 5%
5	Increase d^+ by 20%
6	Increase d^- by 20%
7	Decrease d^+ by 20%
8	Decrease d^- by 20%

The first step in the sensitivity analysis process, involves an increment of the main values of the positive and negative reference points (d^+ and d^-), of each decision alternative by 5% and 20%. The next step is to decrease the same values separately by 5% and 20%.

From the results of the sensitivity analysis (Table 8), it can be seen that the ranking order of the six decision alternatives maintain a consistency when d^+ and d^- of each alternative are increased by 5% and 20%. Such a ranking order also maintains a consistency when d^+ and d^- of each alternative are decreased by 5% and 20%. The results also show that the Closeness Coefficient values of A_1-A_6 consistently increase in Conditions 1, 2, 5 and 6. The Closeness Coefficient values of A_1-A_6 consistently decrease in Conditions 3, 4, 7 and 8. This pattern in the results is to be expected. The model is reasonable and capable of being applied in the analysis of ballast water decision-making alternatives.

Table 8 Results of sensitivity analysis

		A_1			A_2			A_3		
Condition		d^+	d^-	CC_i	d^+	d^-	CC_i	d^+	d^-	CC_i
Main		4.231	0.788	0.157	4.299	0.724	0.144	4.362	0.663	0.132
1	Increase d^+ by 5%	4.442	0.788	0.151	4.514	0.724	0.138	4.580	0.663	0.126
2	Increase d^- by 5%	4.231	0.827	0.164	4.299	0.688	0.138	4.362	0.696	0.138
3	Decrease d^+ by 5%	4.019	0.788	0.164	4.084	0.724	0.151	4.144	0.663	0.138
4	Decrease d^- by 5%	4.231	0.749	0.150	4.299	0.688	0.138	4.362	0.630	0.126
5	Increase d^+ by 20%	5.077	0.788	0.134	4.444	0.724	0.140	5.234	0.663	0.112
6	Increase d^- by 20%	4.231	0.946	0.183	4.299	0.869	0.144	4.362	0.796	0.154
7	Decrease d^+ by 20%	3.385	0.788	0.189	3.439	0.724	0.174	3.490	0.663	0.160
8	Decrease d^- by 20%	4.231	0.630	0.130	4.299	0.579	0.119	4.362	0.530	0.108
Main		A_4			A_5			A_6		
1	Increase d^+ by 5%	4.711	0.545	0.104	4.596	0.649	0.124	4.349	0.870	0.167
2	Increase d^- by 5%	4.487	0.572	0.113	4.377	0.681	0.135	4.142	0.914	0.181

3	Decrease d^+ by 5%	4.263	0.545	113	4.158	0.649	0.135	3.935	0.870	0.181
4	Decrease d^- by 5%	4.487	0.518	0.103	4.377	0.617	0.124	4.142	0.827	0.166
5	Increase d^+ by 20%	5.384	0.545	0.092	5.252	0.649	0.110	4.970	0.870	0.149
6	Increase d^- by 20%	4.487	0.654	0.127	4.377	0.779	0.151	4.142	1.044	0.201
7	Decrease d^+ by 20%	3.599	0.545	0.132	3.502	0.649	0.156	3.314	0.870	0.208
8	Decrease d^- by 20%	4.487	0.436	0.089	4.377	0.519	0.106	4.142	0.696	0.140

6. Conclusion

This model was developed by taking into consideration the legislative requirements of Regulation D2 – D4 of the IMO Ballast Water Convention 2007, as well as the positive contributions of the scientific and technological communities in developing prototype ballast water treatment systems. It is pertinent to state that the inadequacy of data and/or stochastic nature of species assemblages within the global bio-geographical regions pose a great threat to the attainment of the IMO Standards and the utilization of any developed treatment systems for the management of NIS.

It therefore remains uncertain that, a chosen treatment system would be safe, practicable, cost effective, environmentally acceptable, or biologically effective in minimizing the survivability of ballast tank based NIS. This uncertainty can result in the selection of an inappropriate treatment system for the wrong ship type and/or wrong voyage route, thus leading to severe environmental and/or financial consequences.

Powerful MCDM methodologies (AHP and TOPSIS) were applied in this generic model, to solve inherent decision-making problems that could be encountered during the selection process of a ballast water treatment technology under a fuzzy environment. These methodologies have been applied in different specialized fields as stated earlier and found to be effective.

The model developed in this study is by no means conclusive. It is subject to further modification given the acquisition of new data, or current status before its utilization by end-users in the industry. Lastly, a sensitivity analysis was conducted to partially validate the developed model, and establish its ability to respond to changes in input variables.

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