https://doi.org/10.1016/j.chemosphere.2017.10.053

Technology selection for ballast water treatment by multi-stakeholders: A multi-attribute decision analysis approach based on the combined weights and extension theory

Jingzheng Ren[1]

[1]Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China

Correspondence address: Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University Hong Kong SAR, China

Email: jzhren@polyu.edu.hk (J.Z. Ren)

Tel: 852-51665316

Abstract: This objective of this study is to develop a generic multi-attribute decision analysis framework for ranking the technologies for ballast water treatment and determine their grades. An evaluation criteria system consisting of eight criteria in four categories was used to evaluate the technologies for ballast water treatment. The Best-Worst method, which is a subjective weighting method and Criteria importance through inter-criteria correlation method, which is an objective weighting method, were combined to determine the weights of the evaluation criteria. The extension theory was employed to prioritize the technologies for ballast water treatment and determine their grades. An illustrative case including four technologies for ballast water treatment, i.e. Alfa Laval (T_1), Hyde (T_2), Unitor (T_3), and NaOH (T_4), were studied by the proposed method, and the Hyde (T_2) was recognized as the best technology. Sensitivity analysis was also carried to investigate the effects of the combined coefficients and the weights of the evaluation criteria on the final priority order of the four technologies for ballast water treatment. The sum weighted method and the TOPSIS was also employed to rank the four technologies, and the results determined by these two methods are consistent to that determined by the proposed method in this study.

Keywords: ballast water treatment; multi-attribute decision analysis; Best-Worst method; extension theory; criteria system

1. Introduction

Shipping plays a significantly important role for the transportation of global commodity which annually generated about 3-5 billion tonnes of ballast water which is used for ships to ensure the trim, stability and structural integrity (Tsolaki and Diamadopoulos, 2010). The discharge of ballast water can usually lead to various negative impacts on the environment and severe threats to the ecology and human health, because it usually contains many microorganisms, zooplankton, and phytoplankton, etc. (David *et al*., 2013; Tsolaki and Diamadopoulos, 2010). In order to avoid the transferences of harmful and invasive species from the ballast water of ships and mitigate the risks to environment, the international initiatives, namely, Resolution A.868 (20) in 1997 and the International Convention for the Control and Management of Ships' Ballast Water and Sediments have been taken (Pereira *et al*., 2016; IMO, 2004). It will enter into force on 8 September 2017. Meanwhile, various technologies and actions have been implemented. For instance, many countries, i.e. China, German, Sweden, South Africa and Norway, have proposed or been developing the standards for the treatment and discharge of ballast water (Gonçalves and Gagnon, 2012). Accordingly, various technologies have been implemented or under development for the treatment of ballast, i.e. ballast water exchange, physical and mechanical processes, chemical processes, and deoxygenation system (Gonçalves and Gagnon, 2012).

The technologies for ballast water treatment are subject to approval specific IMO processes and will also be tested to ensure the approved technologies can satisfy the related IMO standards (LR, 2007). There are usually various technologies for ballast water treatment which have already been approved, submitted to be approved or under developed. However, the efficacies for killing or removing the microorganisms, the capital costs, the operation and maintenance costs, space, and the impacts on environment of different technologies are different, thus, the decision-makers/stakeholders are usually puzzled to the question: which is the best or the most suitable technology for ballast water treatment among various available scenarios? It is a hard task to answer this question, because various influencing factors need to be considered when selecting a treatment system, i.e. the space required (footprint and volume), power availability, capital and operating costs, integration with existing systems, and health and safety (LR, 2016). Therefore, the selection of the best or the most suitable technology for ballast water treatment for the stakeholders of ships (i.e. ship owner, designers, and operators, etc.) is a multi-attribute decision analysis (MADA) problem. MADA methods are the models which can help the decision-makers to rank multiple alternatives by considering various multiple conflict criteria. All the previous MADA methods are beneficial for ship stakeholders to select the best or the most suitable technology for ballast water treatment. However there are still three research gaps to be filled:

(1) The lack of the MADA method which can handle with the hard criteria and the soft criteria for the evaluation of ballast water treatment simultaneously. Most of the previously published works merely used the data with respect to the hard criteria or scored the technologies with respect to all the criteria subjectively; however, some of these studies cannot fully use the data of the technologies for ballast water treatment with respect to the hard criteria or cannot incorporate soft criteria in decision-making;
(2) The lack of the method for incorporating the subjective weighting and the objective weighting simultaneously. Most of the studies only used the preferences/opinions of the ship stakeholders for determining the weights of the evaluation criteria;
(3) The lack of the method for grading the technologies for ballast water treatment. All these studies can rank the technologies for ballast water treatment; however, it cannot inform the ship stakeholders the priority grades/levels of these technologies.

In order to fill the above-mentioned three research gaps, a novel MADA method was developed by combining the objective weighing method, the subjective weighting method, and the extension theory. Both the objective weighing method and the subjective weighting method were employed for weights determination, thus, both the preferences/opinions of ship stakeholders and the characteristics of the data for decision-making can be incorporated in decision-making. The extension theory was employed to grade the technologies for ballast water treatment and determine their priority order.

2. **Literature reviews**

Many studies have focused on developing the MADA methods for helping the decision-makers/stakeholders to handle this. Karahalios (2017) developed a cost-benefit decision-making tool by combining Analytic Hierarchy Process (AHP) and TOPSIS method for integrating the opinions of ship operators to select the best system for ballast water treatment. Jing *et al*. (2013) developed a novel FSAHP (fuzzy stochastic analytic hierarchy process hierarchy) method to evaluate the technologies for ballast water treatment. PROMETHEE was used to analyze the main technical parameters of the equipment for ballast water treatment (Šateikienė *et al.*, 2015). Satir (2014) employed to use the fuzzy AHP method to select the ballast water treatment. Bakalar (2016) used PROMETHEE to compare different ballast water treatment systems, and five alternative systems were ranked.

As for the evaluation criteria developed for selecting the best or the most suitable technology for ballast water treatment, Karahalios (2017) employed manufacturer longevity, power required, treatment time, system capacity, installation dimensions footprint, installation dimensions height, and use of chemicals. Jing *et al*. (2013) developed an evaluation criteria system which consists of eight criteria for the evaluation of ballast water treatment including efficacy on microorganisms, efficacy on organisms, adaptability to harsh environment, capital cost, O&M

cost, human risk, ecological risk, and waste production. Four main technical parameters (i.e. capacity, dimensions, equipment mass, and energy consumption) were used for evaluating the equipment of ballast water treatment (Šateikienė *et al.*, 2015). Eight criteria including installation cost and operational expenses in cost aspect, approval by IMO and national administration in the aspect of legal basis, installation space, durability-quality, capacity, and gas-proof design in technique aspect were developed for ballast water treatment system (Satir, 2014). Environment pollution footprint, efficacy, guidelines for approval of ballast water management systems (G8) or (procedure for approval of ballast water management systems that make use of Active Substance) G9, treatment in port or on the sea during voyage, and number of methods were used to rank the attentive systems for ballast water treatment (Bakalar, 2016).

In this study, a total of eight evaluation criteria in four categories (technological (TE), environmental & ecological (EE), social (SO), and economic (EC)) were employed to evaluate the technologies for ballast water treatment based on literature reviews and five principles (Wang *et al.*, 2009):

(1) systemic principle: the criteria should roundly reflect the essential characteristic and the whole performance of the technology for ballast water treatment;

(2) Consistency principle: the criteria should be consistent with the decision-making objective-selecting the best technology for ballast water treatment;

(3) Independency principle: the criteria for evaluation of ballast treatment technologies should not have interrelationships at the same criterion level;

(4) Measurability principle: the criteria used for the evaluation of ballast treatment should be measureable in quantitatively or qualitatively; and

(5) Comparability principle: the relative priorities or importance of the criteria should be comparable, and the decision-making result will be more reliable if the comparability of the evaluation criteria is more obvious.

Efficacy (TE_1), footprint (TE_2), and weight (TE_3) are the three criteria to measure technological effectiveness and convenience, residual toxicity (EE_1) is the criterion to measure the integrated environmental & ecological impacts, safety (SO_1) belongs to social category is a measure of the safety status when adopting a technology for ballast water treatment, and electrical load (EC_1), capital cost (EC_2), annual O& M costs (EC_3) were employed to measure the economic performances. These evaluation criteria have been introduced as follows (Monzingo *et al*., 2011):

(1) Technological category

• Efficacy (TE_1): this criterion is a measure of the effectiveness of the technology for removing or killing the organisms in the ballast water.

• Footprint (TE_2): this criterion is used to measure the equipment, the less footprint, the more superior the corresponding technology will be, because the vessel is usually limited by the space when adding an equipment for ballast water treatment.

• Weight (TE_3): this criterion represents the weight of the equipment when adopting a technology for ballast water treatment, and the less weight, the more superior the corresponding will be, because the increase of the weight of a vessel will influence its stability and payload.

(2) Environmental & ecological

• Residual toxicity (EE_1): this criterion is used to measure the potential impacts of the treatment ballast water to environment and ecology upon discharge.

(3) Social

• Safety (SO_1): this criterion is used to measure the safety status when using harmful substances, transferring or storing hazardous chemicals in the process of ballast water treatment.

(4) Economic

• Electrical load (EC_1): operating the system for ballast water treatment usually requires electrical power; however, the small vehicles do not have the ability to generate large amount of electricity. Thus, the less electrical load caused by the system for ballast water treatment, the more superior the corresponding technology will be.

• Capital cost (EC_2): this criterion represents all the initial costs when adopting a treatment system, i.e. the costs for equipment relocation, materials, shipyard labor, and engineering services, etc. (Monzingo *et al.*, 2011).

• Annual O& M costs (EC_3): This criterion includes all the cost annually for operating and maintaining the system for ballast water treatment, i.e. the costs for spare parts, preventive maintenance, operation, consumables, and fuel (Monzingo *et al.*, 2011).

These eights criteria can be divided into two types: the soft-type and the hard-type criteria. The soft-type criteria represent the criteria which cannot be measured or depicted with units due to the inherent characteristics of the criteria or due to the lack of information, and there are three soft-type criteria, i.e. efficacy, residual toxicity, and safety. While the hard-type criteria represent the criteria which can be directly measured and described by numbers with units. In this study, the relative values of the alternative technologies for ballast water treatment were determined by using the Best-Worst method. In addition, it is worth pointing out that this study aims at developing a generic evaluation framework in four categories for selecting the best technology for ballast water treatment among multiple alternative systems; however the users can add more criteria in each of the four categories according to their preferences and the actual conditions.

3. Methods

The framework for selecting the best technology for ballast water treatment was presented in Figure 1, and it consists of four main steps:

Step 1: Determining the alternative technologies for ballast water treatment and the evaluation criteria.

Step 2: Employing the Best-Worst method to determine the relative values of the alternative technologies for ballast water treatment with respect to each evaluation criterion and the subjective weights of the evaluation criteria.

Step 3: Using the criteria importance through inter-criteria correlation method to determine the objective weights of the evaluation criteria.

Step 4: Determining the grade of each of the technologies for ballast water treatment and ranking these technologies.

[Figure 1 near here]

3.1 Weighting methods

Both the objective and the subjective weighting methods were presented in this section, and the weights of the evaluation criteria were determined based on both of the two methods for incorporating the preferences/willingness of the stakeholders as well as the nature of the data in the decision-making matrix.

3.1.1 CRITIC method

Criteria importance through inter-criteria correlation (CRITIC) which was developed by Diakoulaki et al. (1995) is an objective weighting method based on standard deviation and correlation, and it consists of three main steps:

Step 1: Data normalization. The objective of this step is to normalize the data and to transform all the data into the interval between 0 and 1. Assuming that the decision-making matrix contains the information of m alternatives ($A_1, A_2, \cdots, A_m$) with respect to n criteria ($C_1, C_2, \cdots, C_n$), the corresponding matrix can be denoted by Eq.1.

$$\begin{array}{ccccc} & C_1 & C_2 & \cdots & C_n \\ A_1 & a_{11} & a_{12} & \cdots & a_{1n} \\ A_2 & a_{21} & a_{22} & \vdots & a_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & a_{m1} & a_{m2} & \cdots & a_{mn} \end{array} \tag{1}$$

where a_{ij} represents the data of the i-th alternative with respect to the j-th criterion

The criteria can be divided into two types: benefit criteria and cost criteria. Benefit criteria refer to the criteria that have the characteristic that the greater the data with respect to the criteria, the more superior the alternatives will be. On the contrary, cost criteria is the criteria that have the characteristic that the greater the data with respect to the criteria, the less superior the alternatives will be. The data with respect to benefit criteria and cost criteria can be normalized by Eq. 2 and Eq.3, respectively.

$$r_{ij} = \frac{a_{ij} - a_j^{\min}}{a_j^{\max} - a_j^{\min}} \tag{2}$$

$$r_{ij} = \frac{a_j^{\max} - a_{ij}}{a_j^{\max} - a_j^{\min}} \tag{3}$$

where r_{ij} is the normalized value of the i-th alternative with respect to the j-th criterion

$a_j^{\max}$ and $a_j^{\min}$ are the largest and smallest value with respect to the the j-th criterion, and they can be determined by Eq.4 and Eq.5,

$$a_j^{\max} = \max_{i=1,2,\cdots,m} \{a_{ij}\}, j = 1,2,\cdots,n \tag{4}$$

$$a_j^{\max} = \min_{i=1,2,\cdots,m} \{a_{ij}\}, j = 1,2,\cdots,n \tag{5}$$

Step 2: Calculation of standard derivation and correlation. The standard derivation with respect to each criterion can be calculated by Eq.6, and the correlation between each pair of criteria can be determined by Eq.7

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{m} \left(r_{ij} - \overline{r}_j\right)^2}{m}}, j = 1,2,\cdots,n \tag{6}$$

$$\rho_{jk} = \frac{\sum_{i=1}^{m} \left(r_{ij} - \overline{r}_j\right)\left(r_{ik} - \overline{r}_k\right)}{\sqrt{\sum_{i=1}^{m} \left(r_{ij} - \overline{r}_j\right) \sum_{i=1}^{m} \left(r_{ik} - \overline{r}_k\right)}}, j,k = 1,2,\cdots,n \tag{7}$$

where m represents the number of the alternatives, $\overline{r}_j$ represents the average of the values of the m alternatives with respect to the j-th criterion, σ_j is the standard derivation with respect to the *j*-th criterion, and ρ_{jk} is the correlation between the j-th criterion and the k-th criterion.

Step 3: Determination of the weights of the criteria. The amount of information transmitted by the *j*-th criterion can be determined by Eq.8, and the larger the value of the amount of information transmitted by the *j*-th criterion (c_j), the more important the *j*-th criterion will be. Then, the weight of each criterion can be determined by normalizing these values to unity according to Eq.9.

$$c_j = \sigma_j \sum_{k=1}^{n} \left(1 - \rho_{jk}\right), j = 1,2,\cdots,n \tag{8}$$

$$\omega_j^{objective} = c_j \Big/ \sum_{j=1}^{n} c_j, j = 1,2,\cdots,n \tag{9}$$

where c_j represents the amount of information transmitted by the *j*-th criterion, and $\omega_j^{objective}$ is the objective weight of the j-th criterion.

3.1.2 Best-Worst (BW) method

The BW method developed by Rezaei (2015) is a powerful and efficient tool which can incorporate the preferences/opinions of the decision-makers for determining the weights of the criteria through the comparisons of the best criterion to other criteria and that of all the criteria to the worst criterion. Comparing to the Analytic Hierarchy Process (AHP) method developed by Saaty (1978), the BW method has the following advantages:

(1) Less times of comparisons: As for the criteria system with n elements, AHP method requires n(n-1)/2 times of comparisons, while the BW method only need (2n-3) times of comparisons;

(2) Better consistency: it is easier for the users to establish two vectors with better consistency; however it is usually a hard task to establish a comparison matrix with better consistency with the increase of the number of the elements in the criteria systems.

Accordingly, the BW method has been widely used in various fields recently. The BW method consists of four steps (Rezaei, 2015; Rezaei, 2016):

Step 1: Determination of the best (or the most important, the most desirable, denotes by C_b) and the worst (or the least important, the least desirable, denotes by C_w) evaluation criteria .

Step 2: Determining the Best-to-Others (BO) vector by assigning the preference rating of the best criterion over all the other criteria by using the nine-point scale system (the numbers from 1 to 9).

$$BO = \begin{bmatrix} a_{b1} & a_{b2} & \cdots & a_{bn} \end{bmatrix} \tag{10}$$

where $a_{bj} (j = 1, 2, \cdots, n)$ is preference rating of the best criterion (b) over the *j*-th criteria, and $a_{bb} = 1$.

Step 3: Determining the Others-to-Worst (OW) vector by assigning the preference rating of all the criteria over the worst criterion by using the nine-point scale system (the numbers from 1 to 9).

$$OW = \begin{bmatrix} a_{1w} & a_{2w} & \cdots & a_{nw} \end{bmatrix} \tag{11}$$

where $a_{jw}(j = 1, 2, \cdots, n)$ is the preference rating of the j-th criteria over the worst criterion, and $a_{jw} = 1$.

Step 4: Optimizing the weights of all the criteria.

The preference rating $a_{bj}(j = 1, 2, \cdots, n)$ represents the ratio of the weight of the best criterion to the j-th criterion, namely,

$$\frac{\omega_B}{\omega_j^{subjective}} = a_{Bj}(j = 1, 2, \cdots, n) \tag{12}$$

The preference rating $a_{jw}(j = 1, 2, \cdots, n)$ represents the ratio of the j-th criterion to the weight of the worst criterion to, namely,

$$\frac{\omega_j^{subjective}}{\omega_w} = a_{jw}(j = 1, 2, \cdots, n) \tag{13}$$

However, it is usually difficult to satisfy Eq.12 and Eq.13 simultaneously due to the inconsistency existing in the BO and OW vectors.

The objective is to minimize the maximum absolute difference $\left| \frac{\omega_B}{\omega_j^{subjective}} - a_{Bj} \right|$ and $\left| \frac{\omega_j^{subjective}}{\omega_W} - a_{jW} \right|$ for all j for calculating the weights of the n evaluation criteria:

$$\begin{aligned} & \min \max_j \left\{ \left| \frac{\omega_b}{\omega_j^{subjective}} - a_{bj} \right|, \left| \frac{\omega_j^{subjective}}{\omega_w} - a_{jw} \right| \right\} \\ & s.t. \\ & \sum_{j=1}^{n} \omega_j^{subjective} = 1 \\ & \omega_j^{subjective} \geq 0, j = 1, 2, \cdots, n \end{aligned} \tag{14}$$

Programming (14) can be rewritten as:

$$
\begin{aligned}
&\min \xi \\
&s.t. \\
&\left| \frac{\omega_b}{\omega_j^{subjective}} - a_{bj} \right| \le \xi, j = 1,2,\cdots,n \\
&\left| \frac{\omega_j^{subjective}}{\omega_w} - a_{j2} \right| \le \xi, j = 1,2,\cdots,n \\
&\sum_{j=1}^{n} \omega_j^{subjective} = 1 \\
&\omega_j^{subjective} \ge 0, j = 1,2,\cdots,n
\end{aligned}
\tag{15}
$$

where ω_b and ω_w represent the weight of the best criterion and that of the worst criterion, and $\omega_j^{subjective}$ represents the weight of the *j*-th criterion.

Programming (15) is non-linear, and it can also be transformed into linear format for calculating the weights of the n evaluation criteria.

$$
\begin{aligned}
&\min \xi \\
&s.t. \\
&\left| \omega_b - a_{bj}\omega_j^{subjective} \right| \le \xi, j = 1,2,\cdots,n \\
&\left| \omega_j^{subjective} - a_{jw}\omega_w \right| \le \xi, j = 1,2,\cdots,n \\
&\sum_{j=1}^{n} \omega_j^{subjective} = 1 \\
&\omega_j^{subjective} \ge 0, j = 1,2,\cdots,n
\end{aligned}
\tag{16}
$$

After solving programming (16), the optimal weights can then be obtained. The optimum ξ denotes the level of consistency, and the closer the value to zero, the more consistent the BO and OW vectors are.

3.2 Multi-criteria decision making

In this section, the definition of matter-element analysis was firstly presented (see section 3.2.1); then, the MCDM method-extension theory was presented (see section 3.2.2).

3.2.1 Matter-element analysis (Cai, 1983)

The ordered ternary $\mathrm{R} = (N, C, V)$ including matter N, characteristic C and the value V of the characteristic C, which represents a fundamental unit to depict the matter N is called one-dimensional matter element. If the matter N having n characteristics and each characteristic has its corresponding value. Accordingly, the array R is a n-dimensional matter element, as presented in in Eq.1. For instance, a ship whose length, beam and tonnage are 596 ft, 78 ft, and 13599 gross register tons respectively can be expressed by Eq.17.

$$R = \begin{bmatrix} N & , & c_1 & , & v_1 \\ & & c_2 & , & v_2 \\ & & \vdots & , & \vdots \\ & & c_n & , & v_n \end{bmatrix} = (N, C, V) \tag{17}$$

where N is a matter-element vector, C is a characteristic vector, and V is a value vector of C.

$$R_{ship} = \begin{bmatrix} ship & length & 596\,ft \\ & beam & 78\,ft \\ & tonnage & 13599\,tons \end{bmatrix} \tag{18}$$

3.2.2 MCDM method

The proposed MCDM method has six steps, and they were specified as follows (Zheng *et al*, 2009; Ren *et al.*, 2013; Ye, 2009):

Step 1: Determining the combined weights of the evaluation criteria for the assessment of alternative ballast water treatment based on the BW method and CRITIC method. The combined weights of the evaluation criteria can be determined by Eq.19.

$$\omega_j = \alpha \omega_j^{subjective} + (1-\alpha)\omega_j^{objective} \tag{19}$$

where $0 \le \alpha \le 1$ is the combined coefficient.

Step 2: Determining classical domain and the segment domain for grading the technologies for ballast water treatment.

Subs-step 1 of Step 2: classical domain which represents the classical grades of the technologies for ballast water treatment set by the users.

$$R_d=(N_d,C,V_{0d})=\begin{bmatrix} N_d & , & c_{d1} & , & v_{d1} \\ & & c_{d2} & , & v_{d2} \\ & & & , & \\ & & c_{dn} & , & v_{dn} \end{bmatrix}=\begin{bmatrix} N_d & , & c_{d1} & , & <a_{d1},b_{d1}> \\ & & c_{d2} & , & <a_{d2},b_{d2}> \\ & & & , & \\ & & c_{dn} & , & <a_{dn},b_{dn}> \end{bmatrix} \tag{20}$$

Eq.20 means that the technology for ballast water treatment absolutely belongs to the *d*-th grade if and only if the value of the studied technology with respect to each criterion belongs to the corresponding value range of the criterion.

where N_d represents the *d*-th grade, $c_j(j=1,2,\cdots,n)$ represents the *j*-th characteristic/criterion of the matter-element N_d, $<a_{dj},b_{dj}>$ represents a domain, namely the value range of N_d about the characteristic/criterion $c_{dj}(j=1,2,\cdots,n)$, a_{dj} and b_{dj} are lower and upper bound of a classical domain respectively, and suppose there are t grades. R_d is called classical domain, $d=1,2,...,t$.

Subs-step 2 of Step 2:Segment domain.

$$R_P=(P,C,V_P)=\begin{bmatrix} P & , & c_1 & , & v_{p1} \\ & & c_2 & , & v_{p2} \\ & & \cdots & , & \cdots \\ & & c_n & , & v_{pn} \end{bmatrix}=\begin{bmatrix} P & , & c_1 & , & <a_{p1},b_{p1}> \\ & & c_2 & , & <a_{p2},b_{p2}> \\ & & \cdots & , & \cdots \\ & & c_n & , & <a_{pn},b_{pn}> \end{bmatrix} \tag{21}$$

Eq.21 denotes all the possible value range with respect to each criterion.

where P represents the union set of all the grades, $v_{pj}(j=1,2,\cdots,n)$ represents the union set of the value ranges of the characteristic $c_j(j=1,2,\cdots,n)$ in all grades, R_P is called segment domain.

Step 3: Determining the matter-element for assessment.

$$R_x=(X,C,V_x)=\begin{bmatrix} N_x & , & c_1 & , & v_{x1} \\ & & c_2 & , & v_{x2} \\ & & \vdots & , & \vdots \\ & & c_n & , & v_{xn} \end{bmatrix} \tag{22}$$

R_x represents the alternative technology for ballast water treatment to be studied.

where N_x represents the grade of the matter-element (the alternative technology for ballast water treatment) X for assessment, $v_{xj}(j=1,2,\cdots,n)$ is the value of characteristic $c_j(j=1,2,\cdots,n)$ and R_x which represents the matter element for assessment.

Step 4: Correlation degree determination.

The correlation degree of the matter-element (the alternative technology for ballast water treatment) for assessment with respect to each of the classical domains can be determined in this step.

The correlation degree, so-called "dependent degree", of the matter-element for assessment (R_x) the *j*-th characteristic/criterion subjected to the value range of the *j*-th characteristic/criterion in the *d*-th classical domain can be determined by using extension correlation function (see Eq.23). The extension correlation function can also be graphically illustrated (see Figure 2).

$$k_{dj}^{x}=\begin{cases}-\dfrac{\rho(v_{xj},v_{dj})}{\left|v_{dj}\right|} & v_{xj}\subseteq v_{dj}\\ \dfrac{\rho(v_{xj},v_{dj})}{\rho(v_{xj},v_{pj})-\rho(v_{xj},v_{dj})} & v_{xj}\not\subset v_{dj}\end{cases} \tag{23}$$

$$\rho(v_{xj},v_{dj})=\left|v_{xj}-\frac{a_{dj}+b_{dj}}{2}\right|-\frac{b_{dj}-a_{dj}}{2} \tag{24}$$

$$\rho(v_{xj},v_{pj})=\left|v_{xj}-\frac{a_{pj}+b_{pj}}{2}\right|-\frac{b_{pj}-a_{pj}}{2} \tag{25}$$

$$\left|v_{dj}\right|=\frac{\left|b_{dj}-a_{dj}\right|}{2} \tag{26}$$

where $v_{dj}=<a_{dj},b_{dj}>$ and $v_{pj}=<a_{pj},b_{pj}>$

[Figure 2 near here]

Extension correlation function can be used to measure the correlation degree between v_{xj} and v_{dj}. The value of the extension correlation function indicates the degree of v_{xj} belongs to v_{dj}, and the bigger the value, the more dependent it belongs to the classical domains.

Step 5: Calculating the synthesis correlation degree. The synthesis correlation degree which can identify whether the matter for assessment belongs to a certain degree or not from positive to negative can be determined by Eq.27.

$$K_d^x = \sum_{j=1}^{n} \omega_j k_{dj}^x \tag{27}$$

where w_j is the weight of the *j*-th characteristic/criterion, K_d^x represents the synthesis correlation degree of the matter-element for assessment R_x belongs to the *d*-th grade.

Step 6: Determining the grade of each alternative. The largest synthesis correlation degrees of each technology for ballast water treatment can be determined by Eq.28.

$$\overline{K}_d^x = \max_{d=1,2,\ldots,t} \left\{ K_d^x \right\} \tag{28}$$

Then, the grade of the matter-element for assessment could be determined by Eq.28, and it means that the matter-element for assessment R_x is recognized to the class to which the synthesis dependent degree is the maximum.

$$N_x = \arg_{N_d} \left\{ \overline{K}_d^x \right\} \tag{29}$$

where N_x is the final grade of R_x.

4. Case study

Four technologies for ballast water treatment were studied by the proposed method, and they are (Monzingo *et al.*, 2011):

Alfa Laval (T_1): the Alfa Laval Pure Ballast treatment system utilizes a combination of mechanical filtration and photocatalytic reaction to remove or inactivate organisms in the ballast stream;

Hyde (T_2): the Hyde Guardian treatment system utilizes a combination of mechanical filtration and UV sterilization to remove or inactivate organisms in the ballast stream;

Unitor (T_3): the Unitor treatment system employs a combination of cavitation, chemical treatment, and filtration to remove or inactivate organisms in the ballast stream; and

NaOH (T_4): the sodium hydroxide dosing system utilizes an added dosage of sodium hydroxide solution during uptake to increase ballast water pH to levels that are toxic to aquatic organisms.

A total of eight criteria including efficacy (TE_1), footprint (TE_2), and weight (TE_3), residual toxicity (EE_1), safety (SO_1), electrical load (EC_1), capital cost (EC_2), and annual O& M costs (EC_3) were used to determine the grade of each technology and rank these technologies. The BW method was firstly used to determine the subjective weights of the evaluation criteria and the relative performances of the alternative technologies for ballast water treatment. In order to determine the BO and OW vectors accurately, nine participants including two researchers whose research focusing on ballast water treatment, three ship owners, two crews, and three engineers working on ship design were invited to participate in a focus group meeting for determining the BO and OW vectors. Taking the determination of the weights of the four categories as an example:

Step 1: economic (EC) and social (SO) were identified as the most and the least important criteria, respectively.

Step 2: The BO vector can be accordingly determined by assigning the relative preferences of EC over technological (TE), environmental & ecological (EE), social (SO), and economic (EC), respectively. The results were presented in Eq.30.

$$\begin{matrix} TE & EE & SO & EC \\ 2 & 4 & 7 & 1 \end{matrix} \tag{30}$$

Step 3: The OW vector can also be determined by assigning the relative preferences of technological (TE), environmental & ecological (EE), social (SO), and economic (EC) over SO. The results were presented in Eq.31.

$$\begin{matrix} TE & EE & SO & EC \\ 3 & 2 & 1 & 7 \end{matrix} \tag{31}$$

Step 4: The programming for determining the optimal weights of the criteria can be determined:

$$\begin{aligned}
&\min \xi \\
&s.t. \\
&\left|\omega_{EC}^{subjective} - 2\omega_{TE}^{subjective}\right| \le \xi \\
&\left|\omega_{EC}^{subjective} - 4\omega_{EE}^{subjective}\right| \le \xi \\
&\left|\omega_{EC}^{subjective} - 7\omega_{SO}^{subjective}\right| \le \xi \\
&\left|\omega_{TE}^{subjective} - 3\omega_{SO}^{subjective}\right| \le \xi \\
&\left|\omega_{EE}^{subjective} - 2\omega_{SO}^{subjective}\right| \le \xi \\
&\omega_{TE}^{subjective} + \omega_{EE}^{subjective} + \omega_{SO}^{subjective} + \omega_{EC}^{subjective} = 1 \\
&\omega_{TE}^{subjective}, \omega_{EE}^{subjective}, \omega_{SO}^{subjective}, \omega_{EC}^{subjective} \ge 0
\end{aligned} \tag{32}$$

The weights of the four categories can be accordingly determined by solving programming (32), the optimum value of ξ equals to 0.0196, it is very close to zero, thus, the BO and OW vectors have very good consistency. The weights of the four categories were presented in Table 1, and the weights of technological (TE), environmental & ecological (EE), social (SO), and economic (EC) categories are 0.2549, 0.1373, 0.0784, and 0.5294, respectively.

[Table 1 near here]

In a similar way, the local weights of the criteria in each category can also be determined, and the results were presented in Tables 2-3. It is worth pointing out that there is only one criterion in environmental & ecological and social category, so the local weight of the criterion in either of the categories is 1.

[Table 2 near here]

[Table 3 near here]

After determining the weights of the four categories and the local weights of the criteria, the global weights of the criteria can be than determined, and the results were presented in Table 4. Note that the weights are subjective weights which were determined based on the preferences/opinions of the nine experts.

[Table 4 near here]

The data of the alternative technologies for ballast water treatment with respect to efficacy, residual toxicity, and safety can also be obtained by using the BW method, and the results were presented in Tables 5-7. Meanwhile, the data with respect to the other five criteria can be obtained from Monzingo *et al*., (2011).

[Table 5 near here]

[Table 6 near here]

[Table 7 near here]

The decision-making matrix can be determined as presented in Table 8.

[Table 8 near here]

After determining the decision-making matrix, the CRITIC method can be applied to determine the objective weights of the criteria, and the procedures have been specified as follows.

According to Eqs.2-3, the normalized decision-making matrix can be determined. Taking the data of T_1 with respect to efficacy (TE_1) (the element in cell (1,1) of Table 8) and that of T_2 with respect footprint (TE_2) (the element in cell (4,2) of Table 8) as an example:

$$\frac{0.0923 - \min\{0.0923, 0.4846, 0.2538, 0.1692\}}{\max\{0.0923, 0.4846, 0.2538, 0.1692\} - \min\{0.0923, 0.4846, 0.2538, 0.1692\}} = 0 \quad (33)$$

$$\frac{\max\{28, 25, 26, 21\} - 25}{\max\{28, 25, 26, 21\} - \min\{28, 25, 26, 21\}} = 0.4286 \quad (34)$$

In a similar way, all the element in the normalized decision-making matrix can be obtained, and the results were presented in Table 9.

[Table 9 near here]

According to Eq.6, the standard derivation with respect to each criterion can be determined. Taking the standard derivation with respect to efficacy (TE_1) as an example, the average of the values of the four alternative technologies for ballast water treatment with respect to TE_1 is $\frac{0+1+0.4117+0.1960}{4} = 0.4019$, then, the standard derivation with respect to TE_1 can be determined by Eq.35.

$$\sigma_{TE_1} = \sqrt{\frac{(0-0.4019)^2 + (1-0.4019)^2 + (0.4117-0.4019)^2 + (0.1960-0.4019)^2}{4}} = 0.3747 \quad (35)$$

Similarly, all the standard derivations can be obtained, and the results were summarized in Table 10.

[Table 10 near here]

The correlation between each pair of criteria can be determined according to Eq.7, and the results were summarized in Table 11.

[Table 11 near here]

Then, the objective weights of the eight criteria can be determined according to Eq.8 and Eq.9, and the results were summarized in Table 12. Integrating the subjective weights of the eight criteria determined by the BW method, the combined weights can be obtained. The combined coefficient was set as $\alpha = 0.5$, and the combined weights of the criteria were presented in Table 12.

[Table 12 near here]

After determining the decision-making matrix and the weights of the evaluation criteria, the extension theory was employed to grade the four alternative technologies for ballast water treatment. Five classical domains for grading these four alternative technologies for ballast water treatment were set, and they are "Terrible (N_1)" , "Bad (N_2)", "Moderate (N_3)", "Good (N_4)", and "Excellent (N_5)", respectively. These five classical domains were defined in Table 13. According to Eq.21, the segment domain can also be determined, as presented in Eq.36.

[Table 13 near here]

$$R_P = \begin{bmatrix} P & , & TE_1 & , & <0,1> \\ & & EE_1 & , & <0,1> \\ & & SO_1 & , & <0,1> \\ & & TE_2 & , & <0,100> \\ & & TE_3 & , & <500,4200> \\ & & EC_1 & , & <0,50> \\ & & EC_2 & , & <100000,1000000> \\ & & EC_3 & , & <500,5500> \end{bmatrix} \quad (36)$$

According to Eqs.23-27, the synthesis correlation degrees can be then determined, and the results were presented in Table 14.

[Table 14 near here]

According to Eqs.28 -29, it is apparent that both T_1 and T_3 have been recognized as "moderate (N_3)" according to their integrated performances; T_2 has been identified as "good (N_4)"; T_4 has been recognized as "bad (N_2)". Thus, Hyde (T_2) is the most preferable among these four technologies for ballast water treatment. Meanwhile, these four technologies can also be ranked according to the synthesis correlation degrees of the four technologies subjected to "excellent (N_5)", and it is apparent that the synthesis correlation degrees of the four technologies from the smallest to the greatest is Hyde (T_2), NaOH (T_4), Alfa Laval (T_1), and Unitor (T_3). Accordingly, these four technologies for ballast water treatment can be prioritized as Hyde (T_2)＞NaOH (T_4)＞Alfa Laval (T_1)＞Unitor (T_3).

5. Sensitivity analysis and validation

In order to test the influences of the weights of the criteria for evaluating the technologies for ballast water treatment, sensitivity analysis has been carried out by changing the combined coefficients and the weights of the criteria. In addition, another two multi-criteria decision making methods (the sum weighted method and TOPSIS) have also been employed to rank the four technologies for ballast water treatment, and the results determined by these two methods were compared with that determined by the extension theory.

5.1 Sensitivity analysis by changing the combined coefficients

The synthesis correlation degrees of the four technologies for ballast water treatment were investigated by changing the combined coefficients which start from 0 with a step to 1, and the results were presented in Figure 3. It is apparent that changing the combined coefficients will lead to the change of the synthesis correlation degrees of the four technologies for ballast water treatment with respect to each classical domain. However, the grades of the four technologies and their overall ranking are robust. T_1 and T_3 have been recognized as “moderate (N_3)”, T_2 has been identified as “good (N_4)”, and T_4 has been recognized as “bad (N_2)” in all the situations. Therefore, it could be concluded that the results are robust to the combined coefficients.

[Figure 3 near here]

5.2 Sensitivity analysis by changing the weights of the criteria

Sensitivity analysis was also carried out by changing the weights of the criteria for evaluating the four technologies for ballast water treatment, and the following ten cases have been studied:

Case 0: using the combined weights by setting $\alpha = 0.5$;

Case 1: Assigning an equal weight 0.1250 to the eight criteria (TE_1, EE_1, SO_1, TE_2, TE_3, EC_1, EC_2, and EC_3);

Case i (i=2,3,…,9): A dominant weight 0.37 was assigned to each of the eight criteria (TE_1, EE_1, SO_1, TE_2, TE_3, EC_1, EC_2, and EC_3), and the other criteria were assigned an equal weight 0.09.

[Figure 3 near here]

The results of the sensitivity analysis by changing the weights of the criteria were presented in Figure 4, and they reveal that the weights of the evaluation have significant impacts on the grades and the final ranking of the four alternative technologies for ballast water treatment. In other words, changing the weights of the evaluation may alter the he grades and the final ranking of the four alternative technologies for ballast water treatment.

5.3 Validation

In order to validate the results determined by the extension theory, the weighted sum method (SWM) and TOPSIS were also used to determine the priority order of the four technologies for ballast water treatment based on the combined weights and the normalized decision-making matrix by Eqs.2-3, and the results were presented in Table 15.

[Table 15 near here]

The priority ranking of the four technologies for ballast water treatment determined by the extension theory is consistent to that determined by the SWM and the TOPSIS method. To some extent, it could demonstrate that the extension theory is feasible and reliable for ranking the technologies for ballast water treatment. Moreover, the extension theory can determine the grades to which the technologies for ballast water treatment belong to. Accordingly, the decision-makers/stakeholders can know clearly the status of each technology, and it is not only helpful for the decision-makers to select the best or the most sustainable technology for ballast water treatment, but also beneficial for them to know the grades of the technologies according to their integrated priority.

6. Conclusion

The treatment of ballast water in ships which contains various harmful and organisms can effectively reduce the negative impacts to environment and mitigate the contaminations to the ecology. This study aims at proposing a generic multi-criteria decision framework for ranking the technologies for ballast water treatment and determining their grades. The generic criteria systems including eight evaluation criteria in four categories (technological (TE), environmental & ecological (EE), social (SO), and economic (EC)) were used to evaluate the technologies for ballast water treatment. Both the hard criteria and the soft criteria were incorporated in the decision-making. A multi-attribute decision analysis method based on the extension theory was employed to rank the technologies and determine their grades. The subjective weighting method (BW method) and the objective weighting method (CRITIC method) were combined to determine the weights of the criteria. Meanwhile, the BW was also used to determine the data of the technologies for ballast treatment with respect to the soft criteria. Four technologies for ballast water treatment including Alfa Laval (T_1) , Hyde (T_2), Unitor (T_3), and NaOH (T_4) were studied by the proposed framework, and the priority order of the four technologies from the best to the worst is Hyde (T_2), NaOH (T_4), Alfa Laval (T_1), and Unitor (T_3). Sensitivity analysis was also carried to investigate the influences of the combined coefficients as well as the weights of the criteria on the priority order of the four alternatives, and the results reveal that the accurate determination of the weights of the evaluation criteria is of vital importance. All in all, the proposed framework has the following three advantages:

(1) The subjective weighting method and the objective weighting method were combined for weights determination, thus, both the preferences of the decision-makers and the difference between the data of the alternatives can be incorporated in weights determination;
(2) The alternative technologies for ballast water treatment can not only be ranked, but also be graded.

However, this study assumed that all the eight evaluation criteria are independent, and it lacks the considerations of the independent and interacted relationships among the evaluation criteria when determining their weights, and the future works will focus on developing the weighting method which can overlap this gap when determining the weights of the criteria.

References

Bakalar, G. (2016). Comparisons of interdisciplinary ballast water treatment systems and operational experiences from ships. SpringerPlus, 5(1), 240.

Cai, W. (1983). The extension set and incompatible problem. Sci Explor, 3(1), 83A.

Diakoulaki, D., Mavrotas, G., Papayannakis, L., 1995. Determining objective weights in multiple criteria problems: the CRITIC method.Computers & Operations Research, 22(7), 763-770.

David, M., Gollasch, S., Pavliha, M. (2013). Global ballast water management and the "same location" concept: a clear term or a clear issue?. Ecological Applications, 23(2), 331-338.

Gonçalves, A. A., Gagnon, G. A. (2012). Recent technologies for ballast water treatment. Ozone: Science & Engineering, 34(3), 174-195.

International Maritime Organization (IMO). (2004). International Convention for the Control and Management of Ships' Ballast Water and Sediments. This file is avail at: http://www.bsh.de/de/Meeresdaten/Umweltschutz/Ballastwasser/Konvention_en.pdf (Access on 8 May 2017).

Jing, L., Chen, B., Zhang, B., Peng, H. (2013). A hybrid fuzzy stochastic analytical hierarchy process (FSAHP) approach for evaluating ballast water treatment technologies. Environmental Systems Research, 2(1), 10.

Karahalios, H. (2017). The application of the AHP-TOPSIS for evaluating ballast water treatment systems by ship operators. Transportation Research Part D: Transport and Environment, 52, 172-184.

Lioyd's Register (LR). (2007). Ballast water treatment technology. This file is avail at: https://www.intertanko.com/upload/15275/BWThandbook290607.pdf (Access on 8 May 2017).

Lioyd's Register (LR). (2016). Understanding ballast water management. This file is avail at: http://www.lr.org/en/_images/229-77062_Understanding_Ballast_Water_Management_0314_tcm155-248816.0_August%202016.pdf (Access on 8 May 2017).

Monzingo, D.G., Reynolds, K.J., Van Slyke, R.J. (2011). Ballast water treatment system evaluation for small vessels. This file is available at: https://www.nps.gov/isro/learn/nature/upload/10141-01-btws-eval-for-sm-vessels-2.pdf (Access on 6 May 2017)

Pereira, N. N., Colombo, F. B., Chávez, M. I. A., Brinati, H. L., Carreño, M. N. P. (2016). Challenges to implementing a ballast water remote monitoring system. Ocean & Coastal Management, 131, 25-38.

Ren, J., Manzardo, A., Toniolo, S., Scipioni, A. (2013). Sustainability of hydrogen supply chain.

Part II: Prioritizing and classifying the sustainability of hydrogen supply chains based on the combination of extension theory and AHP. International Journal of Hydrogen Energy, 38(32), 13845-13855.

Rezaei, J. (2015). Best-worst multi-criteria decision-making method. Omega, 53, 49-57.

Rezaei, J. (2016). Best-worst multi-criteria decision-making method: Some properties and a linear model. Omega, 64, 126-130.

Satir, T. (2014). Ballast water treatment systems: design, regulations, and selection under the choice varying priorities. Environmental Science and Pollution Research, 21(18), 10686-10695.

Šateikienė, D., Janutėnienė, J., Bogdevičius, M., Mickevičienė, R. (2015). Analysis into the selection of a ballast water treatment system. Transport,30(2), 145-151.

Tsolaki, E., Diamadopoulos, E. (2010). Technologies for ballast water treatment: a review. Journal of Chemical Technology and Biotechnology, 85(1), 19-32.

Wang, J. J., Jing, Y. Y., Zhang, C. F., Zhao, J. H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renewable and Sustainable Energy Reviews, 13(9), 2263-2278.

Ye, J. (2009). Application of extension theory in misfire fault diagnosis of gasoline engines. Expert Systems with Applications, 36(2), 1217-1221.

Zheng, G., Jing, Y., Huang, H., Zhang, X., Gao, Y. (2009). Application of life cycle assessment (LCA) and extenics theory for building energy conservation assessment. Energy, 34(11), 1870-1879.

Figure captions

Figure 1: The framework for selecting the best technology for ballast water treatment

Figure 2: The extension correlation function

Figure 3: The results of sensitivity analysis by changing the combined coefficients

Figure 4: The results of the sensitivity analysis by changing the weights of the criteria

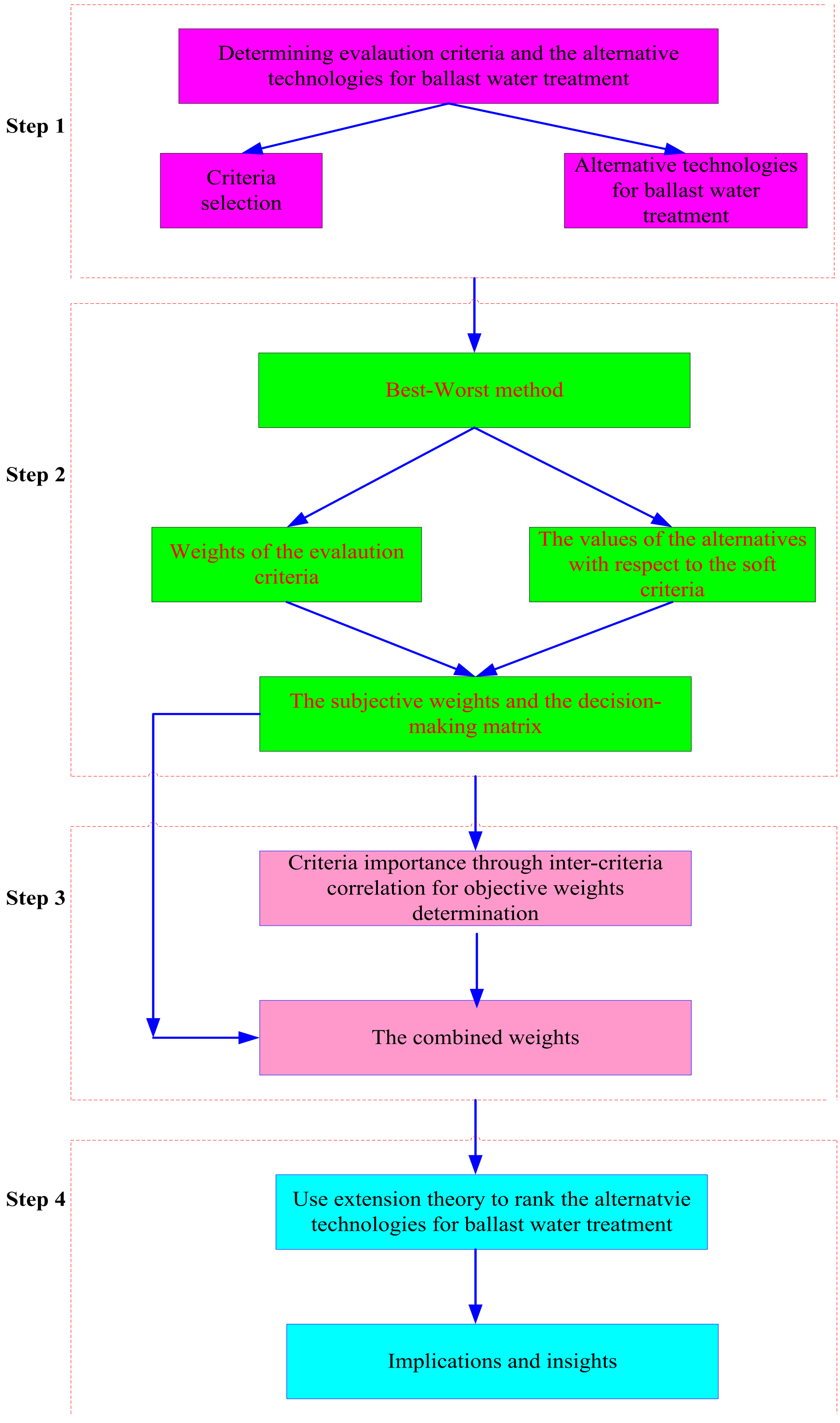

Figure 1: The framework for selecting the best technology for ballast water treatment

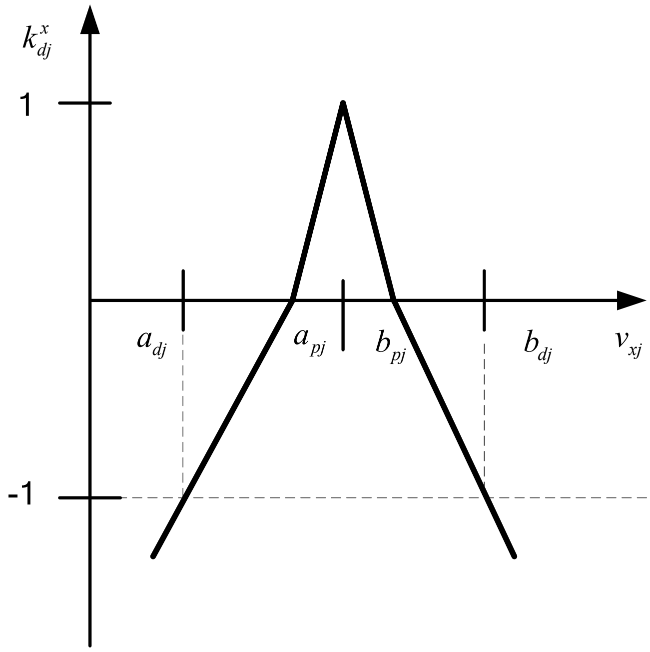

Figure 2: The extension correlation function

Sources: Adapted from Ren *et al*. (2013).

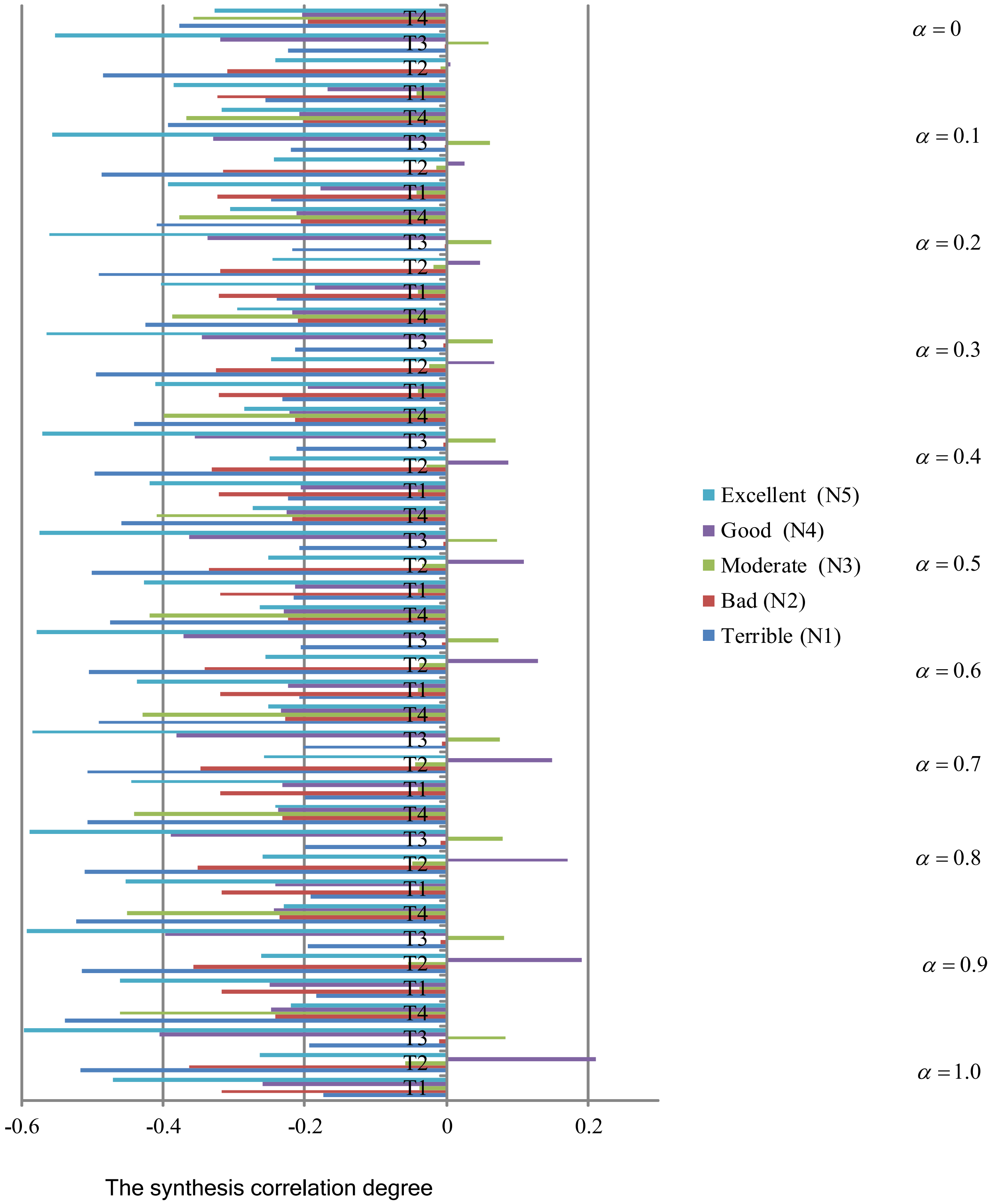

Figure 3: The results of sensitivity analysis by changing the combined coefficients

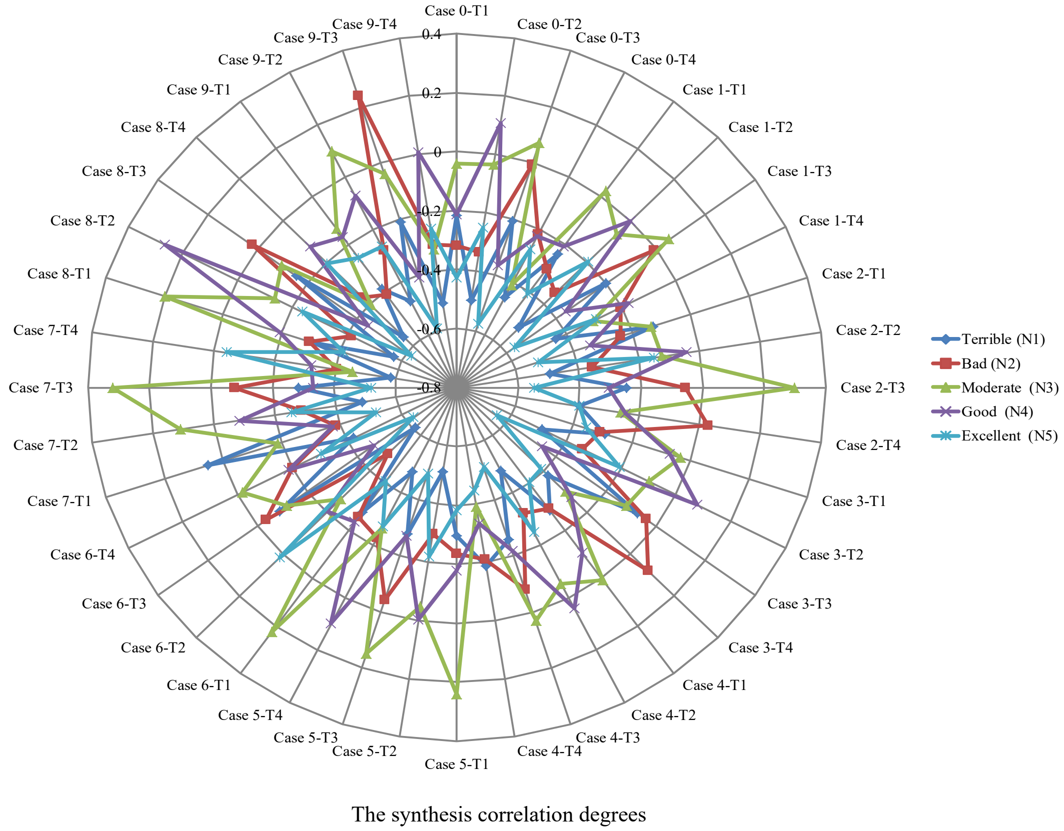

Figure 4: The results of the sensitivity analysis by changing the weights of the criteria

Tables

Table 1: The subjective weights of the four categories

Categories	Technological (TE)	Environmental & ecological (EE)	Social (SO)	Economic (EC)
Weights	0.2549	0.1373	0.0784	0.5294

Table 2: The local weights of the criteria including efficacy (TE_1), footprint (TE_2), and weight (TE_3) in technological category

Criteria	Efficacy (TE_1)	Footprint (TE_2)	Weight (TE_3)
Most important	√		
Least important			√
BO vector	1	4	6
OW vector	6	2	1
Weights	0.7037	0.1852	0.1111

Table 3: The electrical load (EC_1), capital cost (EC_2), and annual O& M costs (EC_3) in economic category

Criteria	Electrical load (EC_1)	Capital cost (EC_2)	Annual O& M costs (EC_3)
Most important		√	
Least important			√
BO vector	2	1	3
OW vector	2	3	1
Weights	0.2917	0.5417	0.1667

Table 4: The global weights of the nine criteria for selecting the alternative technologies for ballast water treatment

	Weights	Criteria	Local weights	Global weights
Technological (TE)	0.2549	Efficacy (TE_1)	0.7037	0.1794
		Footprint (TE_2)	0.1852	0.0472
		Weight (TE_3)	0.1111	0.0283
Environmental & ecological (EE)	0.1373	Residual toxicity (EE_1)	1	0.1373
Social (SO)	0.0784	Safety (SO_1)	1	0.0784
Economic (EC)	0.5294	Electrical load (EC_1)	0.2917	0.1544
		Capital cost (EC_2)	0.5417	0.2868
		Annual O& M costs (EC_3)	0.1667	0.0883

Table 5: The data of the four alternative technologies for ballast water treatment with respect to efficacy

Technologies	T_1	T_2	T_3	T_4
Best		√		
Worst	√			
BO vector	5	1	2	3
OW vector	1	5	3	2
Weights	0.0923	0.4846	0.2538	0.1692

Table 6: The data of the four alternative technologies for ballast water treatment with respect to residual toxicity

Technologies	T_1	T_2	T_3	T_4
Best	√			
Worst			√	
BO vector	1	1	4	3
OW vector	4	4	1	2
Weights	0.3860	0.3860	0.0877	0.1404

Table 7: The data of the four alternative technologies for ballast water treatment with respect to safety

Technologies	T_1	T_2	T_3	T_4
Best	√			
Worst				√
BO vector	1	1	1	4
OW vector	4	4	4	1
Weights	0.3077	0.3077	0.3077	0.0769

Table 8: The decision-making matrix

		T_1	T_2	T_3	T_4
Efficacy (TE_1)	/	0.0923	0.4846	0.2538	0.1692
Residual toxicity (EE_1)	/	0.3860	0.3860	0.0877	0.1404
Safety (SO_1)	/	0.3077	0.3077	0.3077	0.0769
Footprint (TE_2)	sq ft	28	25	26	21
Weight (TE_3)	lbs	3014	972	3750	2879
Electrical load (EC_1)	kW	42	17.2	15	1.5
Capital cost (EC_2)	USD$	465,000	304,000	790,000	199,000
Annual O& M costs (EC_3)	USD$	1434	3244	4062	1735

References: Monzingo *et al*., (2011).

Table 9: The normalized decision-making matrix

	T_1	T_2	T_3	T_4
Efficacy (TE_1)	0.0000	1.0000	0.4117	0.1960
Residual toxicity (EE_1)	1.0000	1.0000	0.0000	0.1767
Safety (SO_1)	1.0000	1.0000	1.0000	0.0000
Footprint (TE_2)	0.0000	0.4286	0.2857	1.0000
Weight (TE_3)	0.2649	1.0000	0.0000	0.3135
Electrical load (EC_1)	0.0000	0.6123	0.6667	1.0000
Capital cost (EC_2)	0.5499	0.8223	0.0000	1.0000
Annual O& M costs (EC_3)	1.0000	0.3113	0.0000	0.8855

Table 10: The standard derivation with respect to each criterion

Criteria	TE_1	EE_1	SO_1	TE_2	TE_3	EC_1	EC_2	EC_3
Standard derivation	0.3747	0.4601	0.4330	0.3642	0.3693	0.3609	0.3781	0.4106

Table 11: The correlation between each pair of criteria

	TE_1	EE_1	SO_1	TE_2	TE_3	EC_1	EC_2	EC_3
TE_1	1.0000	0.2317	0.3172	0.0975	0.7714	0.3084	0.1145	-0.6467
EE_1	0.2317	1.0000	0.4612	-0.4888	0.6788	-0.6793	0.3708	0.3603
SO_1	0.3172	0.4612	1.0000	-0.9058	0.1268	-0.6883	-0.6214	-0.4728
TE_2	0.0975	-0.4888	-0.9058	1.0000	0.1220	0.9057	0.6096	0.1294
TE_3	0.7714	0.6788	0.1268	0.1220	1.0000	0.0498	0.6185	-0.0215
EC_1	0.3084	-0.6793	-0.6883	0.9057	0.0498	1.0000	0.2784	-0.2961
EC_2	0.1145	0.3708	-0.6214	0.6096	0.6185	0.2784	1.0000	0.6257
EC_3	-0.6467	0.3603	-0.4728	0.1294	-0.0215	-0.2961	0.6257	1.0000

Table 12: The objective weights of the eight criteria

Criteria	TE_1	EE_1	SO_1	TE_2	TE_3	EC_1	EC_2	EC_3
Subjective Weights by CRITIC	0.1070	0.1372	0.1870	0.1170	0.0845	0.1264	0.0930	0.1479
Objective weights by BW	0.1794	0.1373	0.0784	0.0472	0.0283	0.1544	0.2868	0.0883
Combined weights when $\alpha = 0.5$	0.1432	0.1372	0.1327	0.0821	0.0564	0.1404	0.1899	0.1181

Table 13: The five classical domains

		Terrible (N_1)	Bad (N_2)	Moderate (N_3)	Good (N_4)	Excellent (N_5)
TE_1	/	[0.00 0.10]	[0.10 0.20]	[0.20 0.30]	[0.30 0.40]	[0.50 1]
EE_1	/	[0.00 0.10]	[0.10 0.20]	[0.20 0.30]	[0.30 0.40]	[0.50 1]
SO_1	/	[0.00 0.10]	[0.10 0.20]	[0.20 0.30]	[0.30 0.40]	[0.50 1]
TE_2	sq ft	[50 100]	[30 50]	[25 30]	[15 25]	[0 15]
TE_3	lbs	[3700 4200]	[3200 3700]	[2700 3200]	[2200 2500]	[500 2200]
EC_1	kW	[30 50]	[20 30]	[10 20]	[5 10]	[0 5]
EC_2	USD$	[800,000 1000,000]	[600,000 800,000]	[400,000 600,000]	[200,000 400,000]	[100,000 200,000]
EC_3	USD$	[4500 5500]	[3500 4500]	[2500 3500]	[1500 2500]	[500 1500]

Table 14: The synthesis correlation degrees of the four technologies for ballast water treatment subject to each grade

	Terrible (N_1)	Bad (N_2)	Moderate (N_3)	Good (N_4)	Excellent (N_5)
T_1	-0.2157	-0.3200	**-0.0402**	-0.2141	-0.4278
T_2	-0.5011	-0.3364	-0.0337	**0.1084**	-0.2528
T_3	-0.2083	-0.0056	**0.0708**	-0.3633	-0.5747
T_4	-0.4582	**-0.2189**	-0.4091	-0.2257	-0.2740

Table 15: The comparison of the results determined by the three methods (the extension theory, SWM, and TOPSIS)

	T_1	T_2	T_3	T_4
Ranking by the extension theory	3	1	4	2
Weighted sum scores by the SWM	0.5074	0.7836	0.3087	0.5870
Ranking by the SWM	3	1	4	2
Closeness coefficients by the TOPSIS	0.5118	0.7301	0.3746	0.5629
Ranking by the TOPSIS	3	1	4	2