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Measuring the sustainability of marine fuels: A fuzzy group multi-criteria decision making approach

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Abstract: The use of alternative energy sources instead of HFO has been recognized as a promising way for reducing emissions from shipping and promoting the development of green shipping. However, it is usually difficult for the decision-making to select the best choice among multiple alternative marine fuels. In order to address this, a complete criteria system for sustainability assessment of alternative marine fuels was firstly established, and a fuzzy group multi-criteria decision making method has been developed to rank the alternative marine fuels by combining fuzzy logarithmic least squares and fuzzy TOPSIS (Technique for Order Performance by Similarity to Ideal Solution). Fuzzy logarithmic least squares method has been employed to determine the weights of the criteria for sustainability assessment, and fuzzy TOPSIS was employed to determine the sustainability order of the alternatives. An illustrative case with three alternative marine fuels including methanol, LNG and hydrogen has been studied by the proposed method, and hydrogen has been recognized as the most sustainable scenario, follows by LNG, and methanol in the descending order. The results show that the proposed method is feasible for prioritizing the alternative marine fuels; it also has the ability to help the decision-makers to select the most sustainable option among multiple marine fuels.

Keywords: Marine fuel; sustainability assessment; group decision making: fuzzy set: multi-criteria decision making

1. Introduction

The increase of the amount of goods transported by ships has caused an increase in the amount of fuel consumption (El Gohary and Seddiek, 2013). The principal exhaust gas emissions from shipping, i.e. CO_2 (Carbon Dioxide), NO_x (Nitric Oxides), SO_x (Oxides of sulfur), CO (Carbon Monoxide), hydrocarbons, and PM (particulate matter), have significant impact on air quality (Eyring *et al*., 2005). After adopting the regulations for the Prevention of Air Pollution from Ships (Annex VI), , many alternative marine fuels have been recognized as promising scenarios to reduce air pollution from ships(Adamchak, and Adede, 2013). Meanwhile, the use of renewable or green energy sources which can substitute the traditional fossil fuels, especially the heavy fuel oil HFO(HFO), were recognized as promising way for achieving green shipping with the increase of the perceptions and attentions of people on environment protection and air quality improvement (Welaya et al., 2011). Laugen (2013) found that liquefied natural gas LNG (LNG) performs marginally better than HFO in life cycle environmental impacts, and it shows that LNG produces 92% less emission than HFO, and the total emissions of LNG and HFO are 127 CO_2-eq/ton km and 130.13 CO_2-eq/ton km, respectively.

Besides LNG, there are also some other renewable or green energy sources which can be used as power of ships, including biodiesel, wind power, liquefied biogas, bio-methanol, and nuclear power. However, different alternative marine fuels have different economic performances, environmental impacts, and social effects. The decision-makers usually have to faceseveral conflicting criteria when choosing the most sustainable marine fuel which has the best integrated performances on economic, environmental, social and technological aspectsamong multiple alternatives. For instance, methanol is a promising environmental-friendly fuel for shipping; however, the current price of methanol is relatively high which seriously hindered the development of methanol propulsion (Lundgren and Wachsmnn, 2014). These are many studies focusing on comparing different alternative marine fuels, and most of these studies aim at comparing the environmental performances of different alternative marine fuels for choosing the most environmental-friendly one. For instance, Brynolf et al. (2014) employed life cycle assessment tool to investigate the environmental impacts of marine fuels including LNG, liquefied biogas, methanol and bio-methanol, and the results shows that the use of liquefied biogas and bio-methanol can reduce the climate change potential. Bengtsson *et al.*(2011) carried out a life cycle environmental impact investigation of four fossil fuels for marine propulsion including HFO, marine diesel oil (MDO), marine gas oil (MGO), and LNG. Øberg (2013) evaluated the life cycle impacts of fuel choice for different marine vessels and their typical operations. Bengtsson (2011) investigated the life cycle environmental impacts of various alternatives to comply with upcoming environmental regulations, including HFOwith a scrubber, marine gas oil with selective catalytic reduction, LNG, and synthetic diesel with selective catalytic reduction, etc. Welaya *et al*. (2011) compared fuel cell and some other marine electric power generation with the considerations of efficiency over a wide range of loads, response to load changes, life, noise, power range, and various emissions. Andersson (2017) has assessed the "well to propeller" energy input and GHG emissions for a number of present and proposed marine fuels including fossil and renewable energy sources. However, the comparison of different marine fuels in environmental impacts or some other issues cannot directly tell the decision-makers/stakeholders which the most sustainable scenario is when facing multiple marine fuel options. Accordingly, Deniz and Zincir (2016) used Analytic Hierarchy Process (AHP) to prioritize methanol, LNG and hydrogen as the alternative marine fuels. Ren and Lützen (2017) developed a novel multi-criteria decision-making method that combines Dempster-Shafer theory and a trapezoidal fuzzy analytic hierarchy process for alternative energy source selection under incomplete information conditions. Geurra and Jenssen (2014) developed a multi-criteria decision analysis (MCDA) model based on AHP for Norwegian maritime sector, marine diesel oil (MDO) and LNG (LNG) have been studied by the proposed model, and the results show that LNG is a more preferred solution compared with MDO. Bulut et al. (2015) improved the applicability of the fuzzy-AHP method by using the rotational priority investigation to rank six alternative marine engines. These studies are of vital importance for the decision-makers/stakeholders to select the best option among multiple alternatives. However, there are still some research gaps which should be filled: (1) The lack of considering the three pillars of sustainability simultaneously when selecting the best or the most suitable marine fuel among multiple alternatives; (2) multiple stakeholders should participate in sustainability assessment of alternative marine fuels to achieve group and democratic decision-making; (3) the convenient method should be developed for the decision-makers/stakeholders to express their opinions and preferences on the relative importance of the criteria for sustainability assessment and the relative performances on the alternative marine fuels with respect to each criterion. Accordingly, sustainability should be incorporated for the selection of marine fuels, and it has been measured as a goal of the alternative marine fuels in this study. As for quantifying sustainability, triple bottom line (TBL) can incorporate not only the traditional measures of profits and return on investment, but also shareholder value to include environmental and social dimensions (Hall, 2011).Thus, sustainability assessment usually needs to measure three pillars including economic, environmental and social categories. As for the sustainability of alternative marine fuels, there is not a unique criteria system, but there are various studies about sustainability assessment of fuels. For instance, Zhou et al. (2007)

employed four indicators including economy indicator (life cycle cost of fuel), environment indicator (global warming potential), energy indicator (the net energy from a fuel) and renewability indicator (non-renewable resource depletion potential) to measure the sustainability of fuels. Tzeng *et al*. (2005) employed eleven criteria in four aspects including social, economic, technological, and transportation to assess the sustainability of alternative-fuel buses for public transportation. Zhou *et al*. (2012) developed a new indicator, CNER (Cost of Net Energy taking into account the Renewability) for life cycle sustainability assessment of fuels by incorporating net energy (NE) output, external cost to society of emissions, total production costs, and the renewability of fuels. Gnanapragasam *et al.* (2010) used three sustainability dimensions (ecological, sociological and technological) and ten indicators for each dimension for measuring the sustainability of hydrogen fuel. In order to fill above-mentioned gaps, fuzzy logarithmic least squares method and fuzzy TOPSIS have been combined to assess the sustainability of different marine fuels in this study..

The residual parts of this study have been organized as follows: Firstly, section 2 provided the models for sustainability assessment of alternative marine fuels, including the criteria for sustainability assessment, fuzzy logarithmic least squares for weights determination, and fuzzy TOPSIS for ranking the alternatives. Then, an illustrative case has been studied by the proposed method in section 3, the results have also been validated, and sensitivity analysis has also been carried out to test the robustness. Finally, this study has been concluded in section 4.

2. Methods

The framework of the group multi-criteria decision making method for sustainability assessment of marine fuels based on fuzzy logarithmic least squares method and fuzzy TOPSIS was presented in Figure 1. The criteria system for sustainability assessment was firstly developed for sustainability assessment of marine fuels. Subsequently, the fuzzy logarithmic least squares method was employed to determine the weights of the criteria for sustainability assessment of marine fuels. Then, the fuzzy TOPSIS method was used to determine the sustainability index of each alternative marine fuel. Finally, the sustainability order of the alternative marine fuels was determined based on the sustainability indices. The criteria system for sustainability assessment, the fuzzy set theory, the fuzzy logarithmic least squares method, and the fuzzy TOPSIS were presented in Section 2.1, Section 2.2, Section 2.3, and Section 2.4, respectively.

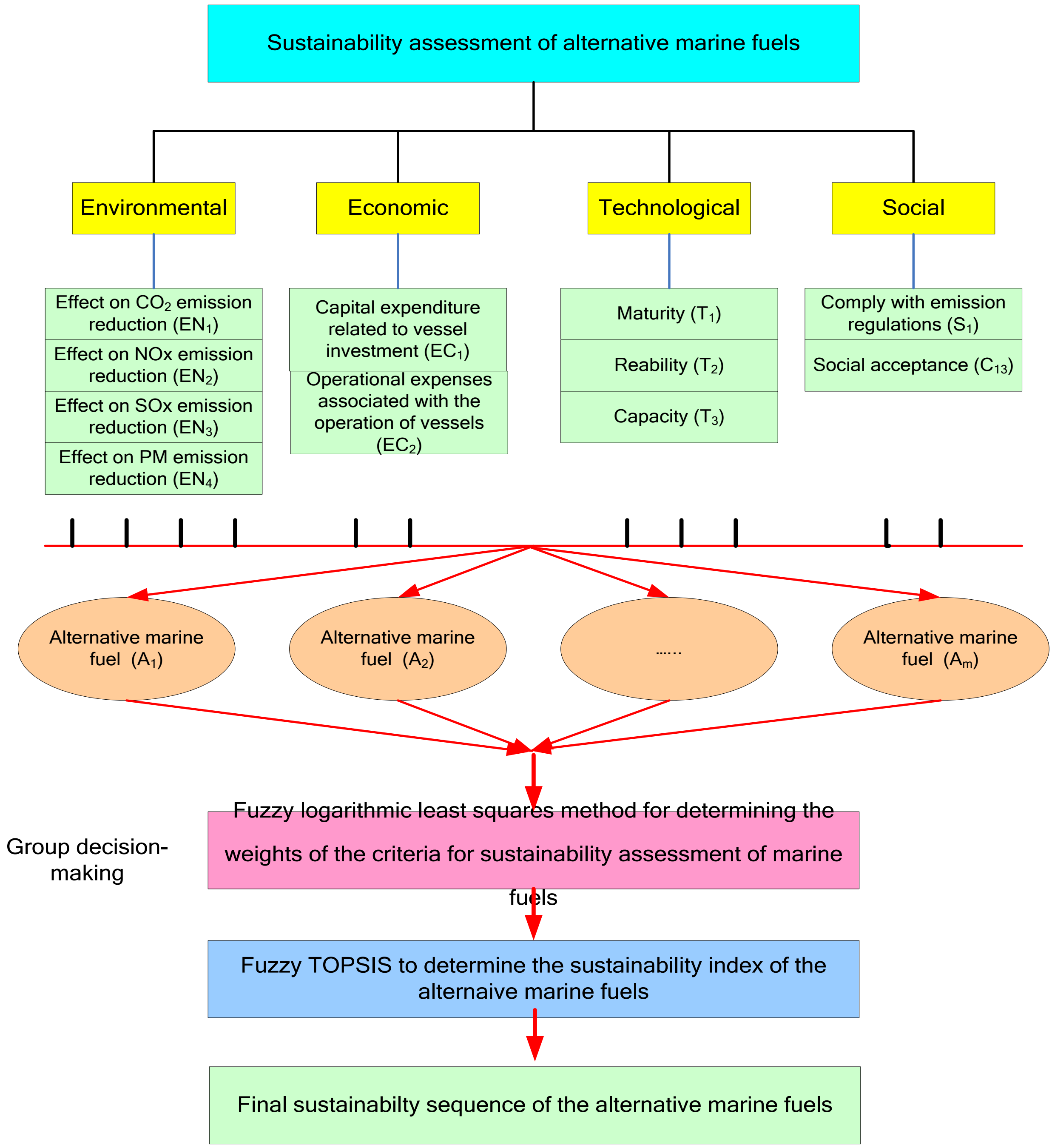

Figure 1: Group decision-making framework for sustainability assessment of marine fuels

2.1 Criteria for sustainability assessment of alternative marine fuels

The criteria system including eleven indicators in four aspects for sustainability assessment of marine fuels was developed (as presented in Table 1) was developed for sustainability of marine fuels. The four dimensions of sustainability are environmental, economic, technological, and social aspects. There are four indicators in environmental aspect, including effect on CO_2 emission reduction, effect on NO_x emission reduction, effect on SO_x emission reduction, and effect on PM emission reduction. The economic dimension consists of two criteria, i.e. capital cost and operational cost. The three criteria including maturity, reliability and capacity are used to measure technological dimension. Social dimension consists of two criteria, namely comply with emission regulations and social acceptance.

Table 1: Criteria for sustainability assessment of marine fuels

Category	Criteria	Abbreviation	Explanations and references
Environmental	Effect on CO_2 emission reduction	EN_1	this criterion is to measure the effect of the alternative marine fuel on CO_2 emission reduction compared with the tradition hydrocarbon fuels for shipping (Deniz and Zincir, 2016)
	Effect on NO_x emission reduction	EN_2	this criterion is to measure the effect of the alternative marine fuel on NO_x emission reduction compared with the tradition hydrocarbon fuels for shipping (Deniz and Zincir, 2016)
	Effect on SO_x emission reduction	EN_3	this criterion is to measure the effect of the

			alternative marine fuel on SO_x emission reduction compared with the tradition hydrocarbon fuels for shipping (Deniz and Zincir, 2016)
	Effect on PM emission reduction	EN_4	this criterion is to measure the effect of the alternative marine fuel on particulate matter (PM) reduction compared with the tradition hydrocarbon fuels for shipping (Deniz and Zincir, 2016)
Economic	Capital cost	EC_1	this criterion refers to capital expenditure related to vessel investment (Guerra and Jenssen, 2014)
	Operational cost	EC_2	this criterion consists of all the operational expenses associate with the operations of vessels (Guerra and Jenssen, 2014)
Technological	Maturity	T_1	this criterion is a measure of the degree of maturity of the technology can refer how widespread it is at both international and national level (Ren et al., 2013)
	Reliability	T_2	alternative fuels have positive or negative impacts on ships, and this criterion is to measure the effect on engine performance (Deniz and Zincir, 2016)
	Capacity	T_3	this criterion is related with global availability

			(Deniz and Zincir, 2016), and it is also crucial to cargo transportation which is subject to engine performance (Guerra and Jenssen, 2014).
Social	Comply with emission regulations	S_1	this criterion is a measure of the degree how the use of the alternative marine fuel comply with emission regulations (Deniz and Zincir, 2016).
	Social acceptance	S_2	this criterion expresses the overview of the opinions related to the use of alternative marine fuel by the society (Ren *et al*., 2016).

2.2 Fuzzy set theory

Fuzzy set theory had been introduced by Zadeh (1965) which has the ability to address uncertainties.

Definition 1. Fuzzy sets (Zadeh, 1965; Yuen and Lau, 2011)

Assume that X is a universal set (or universal discourse) of elements x, then the fuzz set α in X is a set of ordered pairs, it can be mathematically represented by Eq.1. $\mu_\alpha(x)$ is the so-called "membership function" of "grade of membership" which can be defined as

$\mu_\alpha(x): X \to [0 \quad 1]$.Accordingly, if the greater the value of the membership function $\mu_\alpha(x)$, the more certain that x belongs to the fuzzy set α.

$$\alpha = \{(x, \mu_\alpha(x)) \mid x \in X\} \tag{1}$$

where $\mu_\alpha(x)$ is the membership function of x in α.

Fuzzy set theory employed fuzzy number as a bridge to connect human's opinions/judgments which are usually expressed by using the linguistic variables. There are various types of fuzzy numbers, i.e. triangular fuzzy number, trapezoidal fuzzy numbers, and triangular intuitionistic fuzzy numbers. Among these, triangular fuzzy number is the most widely used for its advantages of convenience and accuracy for handling uncertainties. The definition of triangular fuzzy number was presented as follows.

Definition 2. Triangular fuzzy numbers (Chang, 1996)

The triangular fuzzy number $\tilde{a}$ can be defined as a 3-tuple $\left(a^L, a^M, a^U\right)$. The membership of x on $\tilde{a}$ can be defined by Eq.12. Eq.12 can be graphically represented by Figure 2.

$$\mu_{\tilde{a}}(x) = \begin{cases} 0 & x \le a^L \\ \dfrac{x}{a^M - a^L} - \dfrac{a^L}{a^M - a^L} & a^L < x \le a^M \\ \dfrac{a^U}{a^U - a^M} - \dfrac{X}{a^U - a^M} & a^M < x \le a^U \\ 0 & x > a^U \end{cases} \tag{2}$$

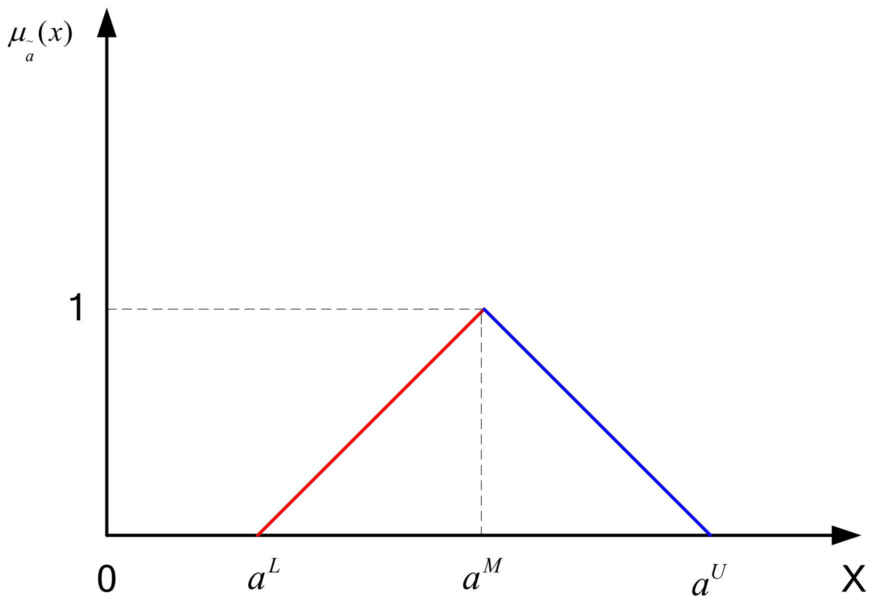

Figure 2: Triangular fuzzy number (a^L, a^M, a^U)

Definition 3. Operations of fuzzy sets (Chang, 1996; Yuen and Lau, 2011)

Assuming there are two triangular fuzzy numbers $\tilde{a} = \left(a^L, a^M, a^U\right)$ and $\tilde{b} = \left(b^L, b^M, b^U\right)$, the operational axioms are:

Addition:

$$\tilde{a} \oplus \tilde{b} = \left(a^L, a^M, a^U\right) \oplus \left(b^L, b^M, b^U\right) = \left(a^L + b^L, a^M + b^M, a^U + b^U\right) \tag{3}$$

Subtraction:

$$\tilde{a} - \tilde{b} = \left(a^L, a^M, a^U\right) - \left(b^L, b^M, b^U\right) = \left(a^L - b^L, a^M - b^M, a^U - b^U\right) \tag{4}$$

Multiplication:

$$\tilde{a} \otimes \tilde{b} = \left(a^L, a^M, a^U\right) \otimes \left(b^L, b^M, b^U\right) = \left(a^L \cdot b^L, a^M \cdot b^M, a^U \cdot b^U\right) \tag{5}$$

$$\tilde{a} \otimes \lambda = \left(a^L, a^M, a^U\right) \otimes \left(\lambda, \lambda, \lambda\right) = \left(\lambda a^L, \lambda a^M, \lambda a^U\right) \tag{6}$$

where $\lambda > 0, \lambda \in R$, and it can be transformed into a fuzzy number $\tilde{\lambda} = \left(\lambda, \lambda, \lambda\right)$.

Division:

$$\tilde{a}/\tilde{b} = \left(a^L, a^M, a^U\right) / \left(b^L, b^M, b^U\right) = \left(a^L/b^L, a^M/b^M, a^U/b^U\right) \tag{7}$$

Reciprocal:

$$\left(\tilde{a}\right)^{-1} = \left(a^L, a^M, a^U\right)^{-1} = \left(1/a^L, 1/a^M, 1/a^U\right) \tag{8}$$

Definition 4. Euclidean distance of two triangular fuzzy numbers (Chen, 2000)

$$d\left(\tilde{a}, \tilde{b}\right) = \sqrt{\left(a^L - b^L\right)^2 + \left(a^M - b^M\right)^2 + \left(a^U - b^U\right)^2} \tag{9}$$

Accordingly, the distance between a fuzzy number $\tilde{a}$ and a crisp real number λ

$$d\left(\tilde{a}, \lambda\right) = \sqrt{\left(a^L - \lambda\right)^2 + \left(a^M - \lambda\right)^2 + \left(a^U - \lambda\right)^2} \tag{10}$$

where $\lambda > 0, \lambda \in R$, and it can be transformed into a fuzzy number $\tilde{\lambda} = \left(\lambda, \lambda, \lambda\right)$.

2.3 Fuzzy logarithmic least squares method

The group fuzzy logarithmic least squares method has the following five steps (Wang *et al.*, 2006; Wang *et al*., 2008) Wang et al. , inclduing: (1) determining the pair-wise comparison matrix determined by each decision-makers/stakeholder; (2) transforming the linguistic variables in the comparsion matrices determined the decision-makers/stakeholder into fuzzy numbers: (3) determining the average pair-wise comparison matrix; (4) establishing the fuzzy logarithmic least squares method (LLSM); (5) determining the overall weights of the criteria.

Step 1: Establishing the pair-wise comparison matrix by using linguistic variables.

A focus group meeting was held to collect the opinions of the decision-makers/stakeholders on the relative importance of one criterion over another; the experts who can represent different groups of stakeholders were invited. Some papers, books and technological reports related to the topic were assigned to the participants as references for helping them to the pair-wise comparison matrix by using linguistic variables.

There are a total of m experts (D_k, k=1,2,…, K) participating in the evaluation of categories/aspects, and there are also n criteria (C_{di}, i=1,2,…, n) in the *d*-th category/aspect. . The experts were asked to use the linguistic variables presented in Table 2 including ‘equally important’ (EI), ‘weakly important’(WI), ‘moderately important’ (MI), ‘moderately plus’ (MP), ‘strongly important’ (SI) ,‘strongly plus’ (SP), ‘very strongly’ (VS), ‘very, very strongly’ (VV), ‘extremely important’ (EX), and their reciprocals (REI, RWI, RMI, RMP, RSI, RSP, RVS, RVV, and REX) to compare the relative importance of one criterion over another. For instance, the abbreviation ‘MI’ will be used to depict the relative preference if one of the participants thought that the relative preference of the *i*-th criterion over the *j*-th criterion in the *d*-th category/aspect is ‘moderately important’ . Accordingly, the relative importance of the *j*-th criterion over the i-th criterion in the *d*-th category/aspect is RMI. Accordingly, the fuzzy comparison matrix $\tilde{A}_d^k$ composed by linguistic variables for determining the weights of the n criteria in the *d*-th category/aspect could be obtained.

Table 2: linguistic variables and the corresponding fuzzy scales for pairwise comparison

linguistic variables	Abbreviations	Fuzzy scales
Equally important	EI	(1, 1, 1)
Weakly important	WI	(1, 2, 3)
Moderately important	MI	(2,3,4)
Moderately plus	MP	(3,4,5)
Strongly important	SI	(4,5,6)
Strongly plus	SP	(5,6,7)
Very strongly	VS	(6,7,8)
Very, very strongly	VV	(7,8,9)
Extremely important	EI	(8,9,9)
Reciprocals of above	Add prefix "R" to the above abbreviations	For a fuzzy number $\left(a^l, a^m, a^u\right)$, its reciprocal can be determined as $\left(\frac{1}{a^u}, \frac{1}{a^m}, \frac{1}{a^l}\right)$

Source: Yuen and Lau, 2011

Step 2: Transforming the linguistic variables in the comparsion matrices determined the decision-makers/stakeholder into fuzzy numbers.

All the linguistic variables in each of the comparison matrix could be transformed into fuzzy numbers. For instance, 'moderately important' (MI) illustrated in Step 1 could be transformed into fuzzy scale (2, 3, 4). Accordingly, (2, 3, 4) was put in the cell (i, j) of $\tilde{A}_d^k$. Similarly, all the other linguistic variables could also be transformed into fuzzy scales. Finally, the comparison matrix could be determined, as presented in Eqs.10-11.

$$\tilde{A}_d^k = \begin{vmatrix} (1,1,1) & \tilde{a}_{12}^k & \cdots & \tilde{a}_{1n}^k \\ 1/\tilde{a}_{12}^k & (1,1,1) & \cdots & \tilde{a}_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{1n}^k & 1/\tilde{a}_{2n}^k & \cdots & (1,1,1) \end{vmatrix} \tag{11}$$

where $\tilde{a}_{jt}^k = \frac{1}{\tilde{a}_{tj}^k} = \left(\frac{1}{a_{tj}^{k,u}}, \frac{1}{a_{tj}^{k,m}}, \frac{1}{a_{tj}^{k,l}} \right)$, $\tilde{A}_d^k$ is the comparison matrix for determining the weights of the criteria in the *d*-th category/aspect by the *k*-th expert, $\tilde{a}_{tj}^k = \left(a_{tj}^{k,l}, a_{tj}^{k,m}, a_{tj}^{k,u} \right)$ is a triangular fuzzy number which represents the relative importance of the *i*-th criterion over the *j*-th criterion in the d-th category/aspect determined by the *d*-th expert, and $a_{tj}^{k,l}$, $a_{tj}^{k,m}$ and $a_{tj}^{k,u}$ are the three elements of the triangular fuzzy number $\tilde{a}_{tj}^k$.

Step 3: Determining the average pair-wise comparison matrix (APWCM).

The average pair-wise comparison matrix could be determined in this step according to the aggregation technique by incorporating the opinions of all the decision-makers/stakeholders, and the weighted geometric mean method which is the most widely used method (Aczel and Alsina , 1986) was used to aggregate the K fuzzy comparison matrices into an average pair-wise comparison matrix, as presented in Eqs.12-13.

$$\tilde{A}_d = \begin{vmatrix} (1,1,1) & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & (1,1,1) & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{2n} & \cdots & (1,1,1) \end{vmatrix} \tag{12}$$

$$\tilde{a}_{tj} = \left(\prod_{k=1}^{k=K} \tilde{a}_{tj}^{k} \right)^{1/K} = \left(\tilde{a}_{tj}^{1} \times \tilde{a}_{tj}^{2} \times \cdots \times \tilde{a}_{tj}^{K} \right)^{1/K} \tag{13}$$

where $\tilde{A}_d$ is the average pair-wise comparison matrix for determining the weights of the criteria in the *d*-th category/aspect, $\tilde{a}_{tj} = \left(a_{tj}^{l}, a_{tj}^{m}, a_{tj}^{u} \right)$ is a triangular fuzzy number which represents the relative importance of the *i*-th criterion over the *j*-th criterion in the d-th category/aspect, and a_{tj}^{l}, a_{tj}^{m}, and a_{tj}^{u} are the three elements of the fuzzy number $\tilde{a}_{tj}$.

Step 4: Establishing the fuzzy logarithmic least squares programming, as presented in Eq.14. The solutions of programming (14) could be obtained by solving the model, thus, the weight of the *j*-th criterion could be obtained $\tilde{\omega}_{ti} = \left(\omega_{ti}^{l}, \omega_{ti}^{m}, \omega_{ti}^{l} \right), t = 1, 2, \cdots, n)$.

$$Minimize\, J = \sum_{t=1}^{n-1} \sum_{j=1, j \neq t}^{n} \left(\left(\ln \omega_{dt}^{l} - \ln \omega_{dj}^{u} - \ln a_{tj}^{l} \right)^2 + \left(\ln \omega_{dt}^{m} - \ln \omega_{dj}^{m} - \ln a_{tj}^{m} \right)^2 + \left(\ln \omega_{dt}^{u} - \ln \omega_{dj}^{l} - \ln a_{tj}^{u} \right)^2 \right)$$
$$\omega_{dt}^{l} + \sum_{j=1, j \neq t}^{n} \omega_{dt}^{u} \geq 1, t = 1, 2, \cdots, n; j = 1, 2, \cdots, n, \quad j \neq t$$
$$\omega_{dt}^{u} + \sum_{j=1, j \neq t}^{n} \omega_{dt}^{l} \leq 1, t = 1, 2, \cdots, n; j = 1, 2, \cdots, n, \quad j \neq t$$
$$\sum_{i=1}^{n} \omega_{dt}^{m} = 1, t = 1, 2, \cdots, n$$
$$\sum_{t=1}^{n} \left(\omega_{dt}^{l} + \omega_{dt}^{u} \right) = 2, t = 1, 2, \cdots, n$$
$$\omega_{dt}^{u} \geq \omega_{dt}^{m} \geq \omega_{dt}^{l} > 0, t = 1, 2, \cdots, n$$
(14)

where $\tilde{\omega}_{dt} = \left(\omega_{dt}^{l}, \omega_{dt}^{m}, \omega_{dt}^{l} \right), t = 1, 2, \cdots, n)$ which is a fuzzy number represents the weight of the *t*-th criterion in the *d*-th category/aspect, and ω_{dt}^{l}, ω_{dt}^{m}, and ω_{dt}^{u} are the three elements of $\tilde{\omega}_{dt}$.

Step 5: Determining the global fuzzy weights of the criteria.

The weights of the criteria in each category/aspect and that of the categories/aspects could also determined in Step 4. Then the global fuzzy weights of the criteria could be determined by Eqs.15-

16.

$$\tilde{\omega}_t = \left(\omega_t^l, \omega_t^m, \omega_t^u\right) = \tilde{\omega}_d \otimes \tilde{\omega}_{dt} = \left(\omega_d^l \omega_{dt}^l, \omega_d^m \omega_{dt}^m, \omega_d^u \omega_{dt}^u\right), t = 1, 2, \cdots, n) \tag{15}$$

$$W = \left[\tilde{\omega}_1, \tilde{\omega}_2, \cdots, \tilde{\omega}_n\right] \tag{16}$$

where $\tilde{\omega}_t$ represents the global fuzzy weight of the *t*-th criterion, $\tilde{\omega}_d$ represents the fuzzy weight of the *d*-th category/aspect, $\tilde{\omega}_{dt}$ represents the local fuzzy weight of the *t*-th criterion in the *d*-th category/aspect.

2.4 Fuzzy TOPSIS

After all the data for assessment criteria were obtained, TOPSIS can also be used to address the multi-criteria decision-making problems by aggregating multiple criteria into a representative index of sustainability (Wang et al., 2009a). The idea of TOPSIS is to rank the prior sequence of the alternative marine fuels by comparing the weighted distance of each alternative to the ideal solution and anti-ideal solution. It holds the thought that the best alternative process has the shortest distance to the ideal solution and the farthest distance to the anti-ideal solution. The traditional TOPSIS cannot address the multi-criteria decision-making problems with uncertainties. In order to address the fuzzy TOPSIS method was developed to address uncertainties, and the weights of the criteria and the elements in the decision-making matrix are all fuzzy numbers.

Assuming that there are a total of K experts participating in the decision-making for assessing m alternatives (A_1, A_2, …, A_m) with the considerations of n criteria (C_1, C_2, …, C_n). There are five steps in the proposed fuzzy TOPSIS based on the works of Wang *et al.* (2009b), Dağdeviren *et al.* (2009), and Amiri (2010):

Step 1: Determining the decision-making matrices using the linguistic variables.

The alternatives with to the criteria could be rated by each expert by using the linguistic variables (see Table 3).

Table 3: linguistic variables and the corresponding fuzzy numbers for rating the alternatives

linguistic variables	Abbreviations	Fuzzy scales
Extremely poor	EP	(1, 1, 2)
Very poor	VP	(1, 2, 3)
Moderately poor	MP	(2,3,4)
Strongly poor	SP	(3,4,5)
Moderate	MO	(4,5,6)
Moderately good	MG	(5,6,7)
Strongly good	SG	(6,7,8)
Very good	VG	(7,8,9)
Extremely good	EG	(8,9,9)

Note: modified from Yuen and Lau, 2011

Step 2: Transforming the linguistic variables in the decision-making matrices into fuzzy scales.

All the decision-making matrices determined in Step 1 could be transformed into fuzzy decision-making matrices, For instance, the fuzzy decision-making matrix determined by the *k*-th expert could be determined, as presented in Eq.17.

$$\tilde{X}^k = \begin{vmatrix} & C_1 & C_2 & \cdots & C_n \\ A_1 & \tilde{x}_{11}^k & \tilde{x}_{12}^k & \cdots & \tilde{x}_{1n}^k \\ A_2 & \tilde{x}_{21}^k & \tilde{x}_{22}^k & \vdots & \tilde{x}_{2n}^k \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & \tilde{x}_{m1}^k & \tilde{x}_{m2}^k & \cdots & \tilde{x}_{mn}^k \end{vmatrix} \tag{17}$$

where $\tilde{x}_{tj}^{k}$ represents the relative performance of the *t*-th alternative with respect to the *j*-th criterion determined by the *k*-th expert.

Step 3: Determining the aggregated decision-making matrix.

The aggregated decision-making matrix could be determined by incorporating all the decision-making matrices determined in Step 2 into a single decision-making matrix, as presented in Eq.18.

$$\tilde{X} = \begin{vmatrix} & C_1 & C_2 & \cdots & C_n \\ A_1 & \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ A_2 & \tilde{x}_{21} & \tilde{x}_{22} & \vdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{vmatrix} \tag{18}$$

where $\tilde{x}_{tj} = \left(x_{tj}^{l}, x_{tj}^{m}, x_{tj}^{u}\right)$ represents the relative performance of the *t*-th alternative with respect to the *j*-th criterion.

The elements in the aggregated decision-making matrix could be obtained by Eq.19.

$$\tilde{x}_{tj} = \left(\prod_{k=1}^{k=K} \tilde{x}_{tj}^{k}\right)^{1/K} = \left(\tilde{x}_{tj}^{1} \otimes \tilde{x}_{tj}^{2} \otimes \cdots \otimes \tilde{x}_{tj}^{K}\right)^{1/K} \tag{19}$$

Step 4: Normalizing the decision-making matrix.

The decision-making matrix presented in Eq.18 could be normalized by Eq. 20 and Eq. 21. It is worth pointing out that the cost-criteria could be transformed into benefit-criteria after the normalization by Eq.19.

$$\tilde{r}_{tj} = \left(\frac{x_{tj}^{l}}{D_j}, \frac{x_{tj}^{m}}{D_j}, \frac{x_{tj}^{u}}{D_j}\right), \mathrm{j} \in B \tag{20}$$

$$\tilde{r}_{tj} = \left(\frac{d_j}{x_{tj}^u}, \frac{d_j}{x_{tj}^m}, \frac{d_j}{x_{tj}^l} \right), \mathrm{j} \in C \tag{21}$$

where

$$D_j = \max_{t=1,2,\cdots,\mathrm{m}} (r_{tj}^u), \mathrm{j} \in B \text{ and } d_j = \min_{t=1,2,\cdots,\mathrm{m}} (r_{tj}^l), \mathrm{j} \in C$$

The benefit-criteria (B) group represents a set of criteria which can benefit the alternatives with the increase of the values about these criteria. On the contrary, the cost-criteria (C) group represents a set of criteria which can harm the alternatives with the increase of the values about these criteria

Step 5: Determining the weighted normalized decision-making matrix.

The weighted normalized decision-making matrix could be obtained by combining the weights of the criteria and the normalized data obtained in Step 4.

$$\tilde{V} = \left| \tilde{v}_{tj} \right|_{m \times n} = \begin{vmatrix} & C_1 & C_2 & \cdots & C_n \\ A_1 & \tilde{\omega}_1 \tilde{r}_{11} & \tilde{\omega}_2 \tilde{r}_{12} & \cdots & \tilde{\omega}_n \tilde{r}_{1n} \\ A_2 & \tilde{\omega}_1 \tilde{r}_{21} & \tilde{\omega}_2 \tilde{r}_{22} & \vdots & \tilde{\omega}_n \tilde{r}_{2n} \\ \vdots & \vdots & \cdots & \ddots & \vdots \\ A_m & \tilde{\omega}_1 \tilde{r}_{m1} & \tilde{\omega}_2 \tilde{r}_{m2} & \cdots & \tilde{\omega}_n \tilde{r}_{mn} \end{vmatrix} \tag{22}$$

where $\tilde{v}_{tj}$ represents the weighted value of the *t*-th alternative with respect to the *j*-th criterion, and $\tilde{\omega}_j$ is the fuzzy weight of the *j*-th criterion determined by the fuzzy logarithmic least squares method.

Step 6: Determining positive ideal solutions and negative ideal solutions.

The positive ideal solutions (PIS) which represent the best possible ideal best alternatives could be obtained by Eq.23 and Eq. 24, while the negative ideal solutions (NIS) which represent the best possible ideal worst alternatives could be obtained by Eq.25 and Eq. 26, respectively.

$$PIS = \left(v_1^+, v_2^+, \cdots, v_n^+\right) \tag{23}$$

$$v_j^+ = \max_{t=1,2,\cdots,m} v_{tj}^u, j = 1, 2, \cdots, n \tag{24}$$

$$NIS = \left(v_1^-, v_2^-, \cdots, v_n^-\right) \tag{25}$$

$$v_j^- = \min_{t=1,2,\cdots,m} v_{tj}^l, j = 1, 2, \cdots, n \tag{26}$$

Step 7: Determining the distance between each alternative to the PIS and that to the NIS.

The distance between each alternative to the PIS and that to the NIS could be obtained by Eq.27 and Eq.28, respectively. For PIS and NIS were crisp numbers, they could be transformed into fuzzy numbers, then, the distance between each alternative and the positive ideal solutions, and that between each alternative and the negative ideal solutions could be determined.

$$d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, v_j^+), i = 1, 2, \cdots, m \tag{27}$$

where d_i^+ represents the distance between the *i*-th alternative and the positive ideal solutions.

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, v_j^-), i = 1, 2, \cdots, m \tag{28}$$

where d_i^- represents the distance between the *i*-th alternative and the negative ideal solutions.

Step 8: Determining the closeness coefficients and ranking the alternatives.

Afterwards, the relative closeness coefficient of each alternative could be determined by Eq.29.

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{29}$$

where CC_i is the closeness coefficient of the *i*-th alternative.

The closeness coefficient reflects the superiority of the alternative (the sustainability of the marine fuels in this study), and the values of the closeness coefficients belong to the interval (0 1), and the near to 1, the more superior the alternative will be; while the closer to 0, the more inferior the alternative will be. Accordingly, the alternatives can be ranked according to the rule that the larger the closeness coefficient is, the better the alternative will be.

3. Case Study

In order to illustrate the proposed group multi-criteria decision-making method for sustainability assessment of alternative marine fuels, three typical alternative marine fuels including methanol, LNG and hydrogen (Deniz and Zincir, 2016) have been studied in this study.

3.1 Phase 1- determining the sustainability criteria, the alternative to be assessed, and the decision-makers

All the eleven criteria in the four dimensions were employed for sustainability assessment. Three representative groups of stakeholders were invited to participate in the decision-making process including ship owners (DM#1), administrators (DM#2), and scholars (DM#3). The stakeholders in each group inquired their colleagues for determining the comparison matrices to calculate the weights of the four dimensions for sustainability assessment and that of the criteria in each dimension, and the relative performances of the alternative marine fuels with respect to each of the criteria for sustainability assessment.

3.2 Phase 2- fuzzy logarithmic least squares method for determining the weights

After determining the weights of the criteria for sustainability assessment and the alternative fuels to be assessed, stage 2 can be carried out. The five steps in stage 2 were presented as follows.

Firstly, the authors asked the coordinator of each group to use linguistic variables to determine the comparison matrix for determining the weights of the four criteria in environmental aspect. The results were presented in Table 4 (**Step 1**).

Table 4: The comparison matrices for determining the weights of the four criteria in environmental aspect by the three groups of stakeholders

DM#1	EN_1	EN_2	EN_3	EN_4
Effect on CO_2 emission reduction (EN_1)	EI	MP	MI	RWI
Effect on NO_x emission reduction (EN_2)	RMP	EI	WI	RSI
Effect on SO_x emission reduction (EN_3)	RMI	RWI	EI	RSP
Effect on PM emission reduction (EN_4)	WI	SI	SP	EI
DM#2	EN_1	EN_2	EN_3	EN_4
Effect on CO_2 emission reduction (EN_1)	EI	SI	MP	RMI
Effect on NO_x emission reduction (EN_2)	RSI	EI	MI	RSP
Effect on SO_x emission reduction (EN_3)	RMP	RMI	EI	RVS
Effect on PM emission reduction (EN_4)	MI	SP	VS	EI
DM#3	EN_1	EN_2	EN_3	EN_4

Effect on CO_2 emission reduction (EN_1)	EI	RWI	RMI	RSI
Effect on NO_x emission reduction (EN_2)	WI	EI	RWI	RMP
Effect on SO_x emission reduction (EN_3)	MI	WI	EI	RMI
Effect on PM emission reduction (EN_4)	SI	MP	MI	EI

The linguistic variables in Table 4 can be transformed into fuzzy numbers according to Table 2. For instance, the linguistic term "MP" can be transformed into (3 4 5) and its reciprocal "RMP" can be transformed into (1/5 1/4 1/3). In a similar way, other linguistic variables can also be transformed into fuzzy numbers, and the results were presented in Table 5 (**Step 2**).

Table 5: The comparison matrices for determining the weights of the four criteria in environmental aspect by the three groups of stakeholders

DM#1	EN_1	EN_2	EN_3	EN_4
EN_1	(1 1 1)	(3 4 5)	(2 3 4)	(1/3 1/2 1)
EN_2	(1/5 1/4 1/3)	(1 1 1)	(1 2 3)	(1/6 1/5 1/4)
EN_3	(1/4 1/3 1/2)	(1/3 1/2 1)	(1 1 1)	(1/7 1/6 1/5)
EN_4	(1 2 3)	(4 5 6)	(5 6 7)	(1 1 1)
DM#2	EN_1	EN_2	EN_3	EN_4
EN_1	(1 1 1)	(4 5 6)	(3 4 5)	(1/4 1/3 1/2)
EN_2	(1/6 1/5 1/4)	(1 1 1)	(2 3 4)	(1/7 1/6 1/5)
EN_3	(1/5 1/4 1/3)	(1/4 1/3 1/2)	(1 1 1)	(1/8 1/7 1/6)
EN_4	(2 3 4)	(5 6 7)	(6 7 8)	(1 1 1)
DM#3	EN_1	EN_2	EN_3	EN_4
EN_1	(1 1 1)	(1/3 1/2 1)	(1/4 1/3 1/2)	(1/6 1/5 1/4)

EN_2	(1 2 3)	(1 1 1)	(1/3 1/2 1)	(1/5 1/4 1/3)
EN_3	(2 3 4)	(1 2 3)	(1 1 1)	(1/4 1/3 1/2)
EN_4	(4 5 6)	(3 4 5)	(2 3 4)	(1 1 1)

According to Table 5, the average pair-wise comparison matrix can be determined according to Eqs.12-13. For instance, the element of cell (1,2) in the average pair-wise comparison matrix could be calculated by using the weighted geometric mean method to incorporate the opinions of the three groups of decision-makers: $\left[(3,4,5)\times(4,5,6)\times\left(\frac{1}{3},\frac{1}{2},1\right)\right]^{\frac{1}{3}}=(1.5874,2.1544,3.1072)$. In a similar way, the elements in the average pair-wise comparison matrix can also be determined, as presented in Table 6 (**Step 3**).

Table 6: The average pair-wise comparison matrix

	EN_1	EN_2	EN_3	EN_4
EN_1	(1 1 1)	(1.5874 2.1544 3.1072)	(1.1447 1.5874 2.1544)	(0.2404 0.3218 0.5000)
EN_2	(0.3218 0.4642 0.6300)	(1 1 1)	(0.8736 1.4422 2.2894)	(0.1682 0.2027 0.2554)
EN_3	(0.4642 0.6300 0.8736)	(0.4638 0.6934 1.1447)	(1 1 1)	(0.1647 0.1995 0.2554)
EN_4	(2.0000 3.1072 4.1602)	(3.9149 4.9324 5.9439)	(3.9149 5.0133 6.0732)	(1 1 1)

The fuzzy logarithmic least squares programming can be established, as presented in Eq.30. After solving this programming, it could be obtained that the minimum value of the objective function equals to 0.5700. And the weights of the four criteria in environmental aspect can also be obtained, as presented in Table 7. In a similar way, the weights of the criteria in the other three aspects and that of the four aspects can also be determined (see Tables 8-11) (**Step 4**).

Finally, the global fuzzy weight of each criterion can be determined by multiplying the local weight of the criterion and the weight of the aspect of the dimension to which the criterion belongs. For instance, the global weight of 'effect on CO_2 emission reduction (EN_1)' can be determined: the local weight of EN_1 (0.1697 0.1995 0.2471) × the weight of the environmental aspect (0.2951 0.3306 0.3622)=the global weight of 'effect on CO_2 emission reduction (EN_1)' (0.0501 0.0660 0.0895). In a similar way, the global weights of other criteria can also be determined, and the results were presented in Table 12 (**Step 5**).

Table 7: The local weights of the four criteria in environmental aspect

	EN_1	EN_2	EN_3	EN_4
Weights	(0.1697 0.1995 0.2471)	(0.0972 0.1182 0.1426)	(0.0893 0.1058 0.1298)	(0.5196 0.5766 0.6047)

$$
\begin{aligned}
&Minimize(J)\\
&J = \left(\ln \omega_{EN_1}^{l} - \ln \omega_{EN_2}^{u} - \ln 1.5874\right)^2 + \left(\ln \omega_{EN_1}^{m} - \ln \omega_{EN_2}^{m} - \ln 2.1544\right)^2 + \left(\ln \omega_{EN_1}^{u} - \ln \omega_{EN_2}^{l} - \ln 3.1072\right)^2\\
&+\left(\ln \omega_{EN_1}^{l} - \ln \omega_{EN_3}^{u} - \ln 1.1447\right)^2 + \left(\ln \omega_{EN_1}^{m} - \ln \omega_{EN_3}^{m} - \ln 1.5874\right)^2 + \left(\ln \omega_{EN_1}^{u} - \ln \omega_{EN_3}^{l} - \ln 2.1544\right)^2\\
&+\left(\ln \omega_{EN_1}^{l} - \ln \omega_{EN_4}^{u} - \ln 0.2404\right)^2 + \left(\ln \omega_{EN_1}^{m} - \ln \omega_{EN_4}^{m} - \ln 0.3218\right)^2 + \left(\ln \omega_{EN_1}^{u} - \ln \omega_{EN_4}^{l} - \ln 0.5000\right)^2\\
&+\left(\ln \omega_{EN_2}^{l} - \ln \omega_{EN_3}^{u} - \ln 0.8736\right)^2 + \left(\ln \omega_{EN_2}^{m} - \ln \omega_{EN_3}^{m} - \ln 1.4422\right)^2 + \left(\ln \omega_{EN_2}^{u} - \ln \omega_{EN_3}^{l} - \ln 2.2894\right)^2\\
&+\left(\ln \omega_{EN_2}^{l} - \ln \omega_{EN_4}^{u} - \ln 0.1682\right)^2 + \left(\ln \omega_{EN_2}^{m} - \ln \omega_{EN_4}^{m} - \ln 0.2027\right)^2 + \left(\ln \omega_{EN_2}^{u} - \ln \omega_{EN_4}^{l} - \ln 0.2554\right)^2\\
&+\left(\ln \omega_{EN_3}^{l} - \ln \omega_{EN_4}^{u} - \ln 0.1647\right)^2 + \left(\ln \omega_{EN_3}^{m} - \ln \omega_{EN_4}^{m} - \ln 0.1995\right)^2 + \left(\ln \omega_{EN_3}^{u} - \ln \omega_{EN_4}^{l} - \ln 0.2554\right)^2\\
&\omega_{EN_1}^{l} + \omega_{EN_2}^{u} + \omega_{EN_3}^{u} + \omega_{EN_4}^{u} \geq 1\\
&\omega_{EN_2}^{l} + \omega_{EN_1}^{u} + \omega_{EN_3}^{u} + \omega_{EN_4}^{u} \geq 1\\
&\omega_{EN_3}^{l} + \omega_{EN_1}^{u} + \omega_{EN_2}^{u} + \omega_{EN_4}^{u} \geq 1\\
&\omega_{EN_4}^{l} + \omega_{EN_1}^{u} + \omega_{EN_2}^{u} + \omega_{EN_3}^{u} \geq 1\\
&\omega_{EN_1}^{u} + \omega_{EN_2}^{l} + \omega_{EN_3}^{l} + \omega_{EN_4}^{l} \leq 1\\
&\omega_{EN_2}^{u} + \omega_{EN_1}^{l} + \omega_{EN_3}^{l} + \omega_{EN_4}^{l} \leq 1\\
&\omega_{EN_3}^{u} + \omega_{EN_1}^{l} + \omega_{EN_2}^{l} + \omega_{EN_4}^{l} \leq 1\\
&\omega_{EN_4}^{u} + \omega_{EN_1}^{l} + \omega_{EN_2}^{l} + \omega_{EN_4}^{l} \leq 1\\
&\omega_{EN_1}^{m} + \omega_{EN_2}^{m} + \omega_{EN_3}^{m} + \omega_{EN_4}^{m} = 1\\
&\omega_{EN_1}^{l} + \omega_{EN_2}^{l} + \omega_{EN_3}^{l} + \omega_{EN_4}^{l} + \omega_{EN_1}^{u} + \omega_{EN_2}^{u} + \omega_{EN_3}^{u} + \omega_{EN_4}^{u} = 2\\
&\omega_{EN_1}^{u} \geq \omega_{EN_1}^{m} \geq \omega_{EN_1}^{l} > 0\\
&\omega_{EN_2}^{u} \geq \omega_{EN_2}^{m} \geq \omega_{EN_2}^{l} > 0\\
&\omega_{EN_3}^{u} \geq \omega_{EN_3}^{m} \geq \omega_{EN_3}^{l} > 0\\
&\omega_{EN_4}^{u} \geq \omega_{EN_4}^{m} \geq \omega_{EN_4}^{l} > 0
\end{aligned}
$$

(30)

Table 8: The matrices for determining the weights of the four criteria in economic aspect

DM#1	EC_1	EC_2
EC_1	EI	MI
EC_2	RMI	EI
DM#2	EC_1	EC_2
EC_1	EI	WI
EC_2	RWI	EI
DM#3	EC_1	EC_2
EC_1	EI	MI
EC_2	RMI	EI
APWCM	EC_1	EC_2
EC_1	(1 1 1)	(1.5874 2.6207 3.6342)
EC_2	(0.2752 0.3816 0.6300)	(1 1 1)
Weights	(0.6135 0.7238 0.7842)	(0.2158 0.2762 0.3865)

Table 9: The matrices for determining the weights of the three criteria in technological aspect

DM#1	T_1	T_2	T_3
T_1	EI	RMI	RWI
T_2	MI	EI	MI
T_3	WI	RMI	EI
DM#2	T_1	T_2	T_3
T_1	EI	RMP	RWI
T_2	MP	EI	WI
T_3	WI	RWI	EI
DM#3	T_1	T_2	T_3
T_1	EI	RWI	RWI
T_2	WI	EI	WI
T_3	WI	RWI	EI
APWCM	T_1	T_2	T_3
T_1	(1 1 1)	(0.2554 0.3467 0.5503)	(0.3333 0.5000 1.0000)
T_2	(1.8172 2.8843 3.9154)	(1 1 1)	(1.2599 2.2894 3.3019)
T_3	(1.0000 2.0000 3.0000)	(0.3029 0.4368 0.7937)	(1 1 1)
Weights	(0.1412 0.1645 0.2217)	(0.4425 0.5535 0.6070)	(0.2019 0.2820 0.3857)

Table 10: The matrices for determining the weights of the four criteria in social aspect

DM#1	S_1	S_2
S_1	EI	EI
S_2	EI	EI
DM#2	S_1	S_2
S_1	EI	MI
S_2	RMI	EI
DM#3	S_1	S_2
S_1	EI	WI
S_2	RWI	EI
APWCM	EC_1	EC_2
EC_1	(1 1 1)	(1.2599 1.8171 2.2894)
EC_2	(0.4368 0.5503 0.7937)	(1 1 1)
Weights	(0.5575 0.6450 0.6960)	(0.3040 0.3550 0.4425)

Table 11: The matrices for determining the weights of the four aspects of sustainability

DM#1	EN	EC	T	S
EN	EI	RWI	WI	MI
EC	WI	EI	MI	MP
T	RWI	RMI	EI	WI
S	RMI	RMP	RWI	EI
DM#2	EN	EC	T	S
EN	EI	EI	MI	MI
EC	EI	EI	WI	MI
T	RMI	RWI	EI	WI
S	RMI	RMI	RWI	EI
DM#3	EN	EC	T	S
EN	EI	RMI	MP	SI
EC	MI	EI	WI	MI
T	RMP	RWI	EI	WI
S	RSI	RMI	RWI	EI
APWCM	EN	EC	T	S
EN	(1 1 1)	(0.4368 0.5503 0.7937)	(1.8171 2.8845 3.9149)	(2.5198 3.5569 4.5789)
EC	(1.2599 1.8172 2.2894)	(1 1 1)	(1.2599 2.2894 3.3019)	(2.2894 3.3019 4.3089)
T	(0.2554 0.3467	(0.3029 0.4368	(1 1 1)	(1 2 3)

	0.5503)	0.7937)		
S	(0.2184 0.2811 0.3969)	(0.2321 0.3029 0.4368)	(0.3333 0.50000 1)	(1 1 1)
Weights	(0.2951 0.3306 0.3622)	(0.3329 0.4129 0.4586)	(0.1174 0.1591 0.2224)	(0.0855 0.0974 0.1260)

Table 12: The local weights of the four criteria in environmental aspect

Aspect	Weights	Criteria	Local weights	Global weights
	(0.2951 0.3306 0.3622)	EN_1	(0.1697 0.1995 0.2471)	(0.0501 0.0660 0.0895)
		EN_2	(0.0972 0.1182 0.1426)	(0.0287 0.0391 0.0516)
		EN_3	(0.0893 0.1058 0.1298)	(0.0264 0.0350 0.0470)
EN		EN_4	(0.5196 0.5766 0.6047)	(0.1533 0.1906 0.2190)
	(0.3329 0.4129 0.4586)	EC_1	(0.6135 0.7238 0.7842)	(0.2042 0.2989 0.3596)
EC		EC_2	(0.2158 0.2762 0.3865)	(0.0718 0.1140 0.1772)
	(0.1174 0.1591 0.2224)	T_1	(0.1412 0.1645 0.2217)	(0.0166 0.0262 0.0493)
		T_2	(0.4425 0.5535 0.6070)	(0.0519 0.0881 0.1350)
T		T_3	(0.2019 0.2820 0.3857)	(0.0237 0.0449 0.0858)
	(0.0855 0.0974 0.1260)	S_1	(0.5575 0.6450 0.6960)	(0.0477 0.0628 0.0877)
S		S_2	(0.3040 0.3550 0.4425)	(0.0260 0.0346 0.0558)

3.3 Phase 3- fuzzy TOPSIS for determining the sustainability order of the alternative maritime fuels

After determining the weights of the criteria, fuzzy TOPSIS method can be used to rank the alternative maritime fuels (Stage 2). The five steps of stage 2 were presented in Stage 2. The decision-making matrices using the linguistic variables were firstly determined by the three groups of decision-makers, as presented in Table 13 (**Step** 1).

Table 13: The decision-making matrix determined by the three groups of decision-makers for sustainability assessment of the alternative maritime fuels

	Methanol	LNG	Hydrogen
Effect on CO_2 emission reduction (EN_1)	SP,MP,MP	VG,SG,VG	EG,EG,EG
Effect on NO_x emission reduction (EN_2)	MO,MG,SG	SG,VG,VG	VP,MP,MP
Effect on SO_x emission reduction(EN_3)	MG,VG,MG	VG,VG,MO	MO,VP,VP
Effect on PM emission reduction(EN_4)	VP,SP,MP	MO,MO,MG	MP,SP,MO
Capital cost(EC_1)	MG,MG,SG	EP,VP,VP	SG,VG,EG
Operational cost(EC_2)	SP.MO,MP	MG,SG,VG	VP,MP.EP
Maturity(T_1)	MP,SP,SP	MG,MO,SG	EP,EP,VP
Reliability(T_2)	VP,EP,MP	SG,EG,EG	VG,EG,MG
Capacity(T_3)	MP,SP,SP	EP,VP,MP	MO,MO,MO
Comply with emission regulations(S_1)	MO,MG,SP	VG,VG,EG	VP,VP,MP
Social acceptance(S_2)	SG,EG,VG	EG,EG,MG	EG,VG,VG

According to Table 3, all the linguistic variables in Table 13 can be transformed into fuzzy numbers. For instance, "SP" and "MP" can be transformed into fuzzy numbers (3, 4, 5) and (2,3,4). In a similar way, all the linguistic variables can be transformed into fuzzy numbers, and the results were presented in Table 14 (**Step 2**).

Table 14: The decision-making matrix determined by the three groups of decision-makers for sustainability assessment of the alternative maritime fuels

	Methanol	LNG	Hydrogen
EN_1	(3, 4, 5),(2, 3, 4),(2, 3, 4)	(7, 8, 9),(6, 7, 8),(7, 8, 9)	(8, 9, 9),(8, 9, 9),(8, 9, 9)
EN_2	(4, 5, 6),(5, 6, 7),(6, 7, 8)	(6, 7, 8),(7, 8, 9),(7, 8, 9)	(1, 2, 3),(2, 3, 4),(2, 3, 4)
EN_3	(5, 6, 7),(7, 8, 9),(5, 6, 7)	(7, 8, 9),(7, 8, 9),(4, 5, 6)	(4, 5, 6),(1, 2, 3),(1, 2, 3)
EN_4	(1, 2, 3),(3, 4, 5),(2, 3, 4)	(4, 5, 6),(4, 5, 6),(5, 6, 7)	(2, 3, 4),(3, 4, 5),(4, 5, 6)
EC_1	(5, 6, 7),(5, 6, 7),(6, 7, 8)	(1, 1, 2),(1, 2, 3),(1, 2, 3)	(6, 7, 8),(7, 8, 9),(8, 9, 9)
EC_2	(3, 4, 5).(4, 5, 6),(2, 3, 4)	(5, 6, 7),(6, 7, 8),(7, 8, 9)	(1, 2, 3),(2, 3, 4).(1, 1, 2)
T_1	(2, 3, 4),(3, 4, 5),(3, 4, 5)	(5, 6, 7),(4, 5, 6),(6, 7, 8)	(1, 1, 2),(1, 1, 2),(1, 2, 3)
T_2	(1, 2, 3),(1, 1, 2),(2, 3, 4)	(6, 7, 8),(8, 9, 9),(8, 9, 9)	(7, 8, 9),(8, 9, 9),(5, 6, 7)
T_3	(2, 3, 4),(3, 4, 5),(3, 4, 5)	(1, 1, 2),(1, 2, 3),(2, 3, 4)	(4, 5, 6),(4, 5, 6),(4, 5, 6)
S_1	(4, 5, 6),(5, 6, 7),(3, 4, 5)	(7, 8, 9),(7, 8, 9),(8, 9, 9)	(1, 2, 3),(1, 2, 3),(2, 3, 4)
S_2	(6, 7, 8),(8, 9, 9),(7, 8, 9)	(8, 9, 9),(8, 9, 9),(5, 6, 7)	(8, 9, 9),(7, 8, 9),(7, 8, 9)

The aggregated decision-making matrix can be determined according to Eqs.18-19. For instance, the data of methanol with respect to 'effect on CO_2 emission reduction (EN_1)' can be determined by:

$$\begin{aligned} &\left[(3,\ 4,\ 5)\otimes(2,\ 3,\ 4)\otimes(2,\ 3,\ 4)\right]^{1/3} \\ &=\left((3\times2\times2)^{1/3},\ (4\times3\times3)^{1/3},\ (5\times5\times4)^{1/3}\right) \\ &=(2.2894,\ 3.3019,\ 4.3089) \end{aligned} \tag{31}$$

Similarly, other elements of the aggregated decision-making matrix could also be determined, as presented in Table 15 (**Step 3**).

Table 15: The aggregated decision-making matrix by incorporating the opinions of the three groups of decision-makers for sustainability assessment of the alternative maritime fuels

	Methanol	LNG	Hydrogen
EN_1	(2.2894 3.3019 4.3089)	(6.6494 7.6517 8.6535)	(8.0000 9.0000 9.0000)
EN_2	(4.9324 5.9439 6.9521)	(6.6494 7.6517 8.6535)	(1.5874 2.6207 3.6342)
EN_3	(5.5934 6.6039 7.6117)	(5.8088 6.8399 7.8622)	(1.5874 2.7144 3.7798)
EN_4	(1.8171 2.8845 3.9149)	(4.3089 5.3133 6.3164)	(2.8845 3.9149 4.9324)
EC_1	(5.3133 6.3164 7.3186)	(1.0000 1.5874 2.6207)	(6.9521 7.9581 8.6535)
EC_2	(2.8845 3.9149 4.9324)	(5.9439 6.9521 7.9581)	(1.2599 1.8171 2.8845)
T_1	(2.6207 3.6342 4.6416)	(4.9324 5.9439 6.9521)	(1.0000 1.2599 2.2894)
T_2	(1.2599 1.8171 2.8845)	(7.2685 8.2768 8.6535)	(6.5421 7.5595 8.2768)
T_3	(2.6207 3.6342 4.6416)	(1.2599 1.8171 2.8845)	(4.0000 5.0000 6.0000)
S_1	(3.9149 4.9324 5.9439)	(7.3186 8.3203 9.0000)	(1.2599 2.2894 3.3019)
S_2	(6.9521 7.9581 8.6535)	(6.8399 7.8622 8.2768)	(7.3186 8.3203 9.0000)

It is worth pointing out that all the data presented in Table 15 make all the criteria be benefit-criteria, because the decision-makers used linguistic variables and fuzzy numbers to depict the relative performances of the alternatives with respect to each criterion. Accordingly Eq.20 was employed to normalize the data. For instance, (2.2894 3.3019 4.3089) which indicates the relative performance of the first alternative marine fuel 'methanol' with respect to 'effect on CO_2 emission reduction (EN_1)' can be normalized by Eq.32. In a similar way, all the data presented in Table 15 can be normalized, and the results were presented in Table 16 (**Step 4**).

$$
\begin{aligned}
&\frac{(2.2894,\ 3.3019,\ 4.3089)}{\max\{4.3089,\ 8.6535,\ 9.0000\}} \\
&= \frac{(2.2894,\ 3.3019,\ 4.3089)}{9.0000} \\
&= (0.2544,\ 0.3669,\ 0.4788)
\end{aligned} \tag{32}
$$

Table 16: The normalized decision-making matrix

	Methanol	LNG	Hydrogen
EN_1	(0.2544 0.3669 0.4788)	(0.7388 0.8502 0.9615)	(0.8889 1.0000 1.0000)
EN_2	(0.5700 0.6869 0.8034)	(0.7684 0.8842 1.0000)	(0.1834 0.3028 0.4200)
EN_3	(0.7114 0.8400 0.9681)	(0.7388 0.8700 1.0000)	(0.2019 0.3452 0.4808)
EN_4	(0.2877 0.4567 0.6198)	(0.6822 0.8412 1.0000)	(0.4567 0.6198 0.7809)
EC_1	(0.6140 0.7299 0.8457)	(0.1156 0.1834 0.3028)	(0.8034 0.9196 1.0000)
EC_2	(0.3625 0.4919 0.6198)	(0.7469 0.8736 1.0000)	(0.1583 0.2283 0.3625)
T_1	(0.3770 0.5227 0.6677)	(0.7095 0.8550 1.0000)	(0.1438 0.1812 0.3293)
T_2	(0.1456 0.2100 0.3333)	(0.8399 0.9565 1.0000)	(0.7560 0.8736 0.9565)
T_3	(0.4368 0.6057 0.7736)	(0.2100 0.3029 0.4808)	(0.6667 0.8333 1.0000)
S_1	(0.4350 0.5480 0.6604)	(0.8132 0.9245 1.0000)	(0.1400 0.2544 0.3669)
S_2	(0.7725 0.8842 0.9615)	(0.7600 0.8736 0.9196)	(0.8132 0.9245 1.0000)

After determining the normalized decision-making matrix, the weighted normalized decision-making matrix can be obtained by Eq.22. For instance, (0.2544 0.3669 0.4788) which indicates the normalized relative performance of the first alternative marine fuel 'methanol' with respect to 'effect on CO_2 emission reduction (EN_1)' can be transformed into (0.0127 0.0242 0.0428) by Eq.33. Similarly, the data of the alternative marine fuels with respect to each criterion in Table 16 can be weighted by multiplying the data and the corresponding weight, and the results were presented in Table 17 (**Step 4**).

$$\begin{aligned}&\left(0.2544,\ 0.3669,\ 0.4788\right)\otimes\left(0.0501,\ 0.0660,\ 0.0895\right)\\&=\left(0.0127,\ 0.0242,\ 0.0428\right)\end{aligned} \tag{33}$$

Table 17: The weighted normalized decision-making matrix

	Methanol	LNG	Hydrogen
EN_1	(0.0127 0.0242 0.0428)	(0.0370 0.0561 0.0861)	(0.0445 0.0660 0.0895)
EN_2	(0.0164 0.0269 0.0415)	(0.0221 0.0346 0.0516)	(0.0053 0.0118 0.0217)
EN_3	(0.0188 0.0294 0.0455)	(0.0195 0.0304 0.0470)	(0.0053 0.0121 0.0226)
EN_4	(0.0441 0.0870 0.1357)	(0.1046 0.1603 0.2190)	(0.0700 0.1181 0.1710)
EC_1	(0.1254 0.2182 0.3041)	(0.0236 0.0548 0.1089)	(0.1641 0.2749 0.3596)
EC_2	(0.0260 0.0561 0.1098)	(0.0536 0.0996 0.1772)	(0.0114 0.0260 0.0642)
T_1	(0.0063 0.0137 0.0329)	(0.0118 0.0224 0.0493)	(0.0024 0.0047 0.0162)
T_2	(0.0076 0.0185 0.0450)	(0.0436 0.0843 0.1350)	(0.0392 0.0770 0.1291)
T_3	(0.0104 0.0272 0.0664)	(0.0050 0.0136 0.0412)	(0.0158 0.0374 0.0858)
S_1	(0.0207 0.0344 0.0579)	(0.0388 0.0581 0.0877)	(0.0067 0.0160 0.0322)
S_2	(0.0201 0.0306 0.0537)	(0.0198 0.0302 0.0513)	(0.0211 0.0320 0.0558)

Subsequently, the positive ideal solutions and negative ideal solutions can be obtained by Eqs.23-26, and they are:

$$PIS=\left(0.0895,0.0516,0.0470,0.2190,0.3596,0.1772,0.0493,0.1350,0.0858,0.0877,0.0558\right) \tag{34}$$

$$NIS = (0.0127, 0.0053, 0.0053, 0.0441, 0.0236, 0.0114, 0.0024, 0.0076, 0.0050, 0.0067, 0.0198) \quad (35)$$

Then, the distance between each alternative to the PIS and that to the NIS can be determined by Eq.27 and Eq.28, and the results were presented in Table 18. Finally, the relative closeness coefficient of each alternative can be determined by Eq.29, it is apparent that the sustainability order of the three alternative marine fuels from the best to the least is hydrogen, LNG, and methanol.

Table 18: The final results of fuzzy TOPSIS for ranking the three alternative marine fuels

	Methanol	LNG	Hydrogen
d_i^+	1.3920	1.2908	1.2624
d_i^-	0.9239	1.0751	1.0920
CC_i	0.3989	0.4544	0.4638
Ranking	3	2	1

Hydrogen has been recognized as the most sustainable marine fuel among these three alternatives by the developed method, this result is reasonable for the following reasons:(1) better environmental performance: there is no waste gas emissions (GHG, SO_x, and NO_x) when using hydrogen the fuel for shipping LNG and methanol have relatively worse performances on environmental and renewability aspects compared with hydrogen; (2) higher renewability: hydrogen can be produced from a number of renewable resources, i.e. water electrolysis based on wind power, electrolysis based on hydropower, and electrolysis based on nuclear power, et al. Thus, it has high potential of renewability when adopting renewable sources for hydrogen production; (3) more compliance with governmental policies: hydrogen as a clean energy carrier does not generate any emissions during its oxidation; accordingly, it is in full compliance with the International Maritime Organization (IMO) regulations which aims at emissions mitigation from shipping; (4) higher social acceptability: hydrogen as an alternative energy source for shipping has high social acceptability for its advantage for environment protection; (5) methanol also has the best performance on capital cost among these three alternative marine fuels. Meanwhile, this criterion was also assigned the highest weight by the fuzzy logarithmic least squares method.

3.4 Discussion

In this section, the weighted sum method (WSM) was firstly employed to validate the results determined by fuzzy TOPSIS method; then, sensitivity analysis was carried out to test the robustness.

In order to validate the results determined by fuzzy TOPSIS method, the WSM was also employed to rank these three alternative marine fuels. Based on WSM presented in the work of Ren et al. (2016), the weighted sum with respect to each of the alternative marine fuels can be determined as presented in Table 19. Then, the sustainability order of the alternative marine fuels can be determined by transforming the fuzzy weighted sum into crisp numbers by the CoG method (Ren *et al*., 2015). It is apparent that the results determined by WSM are consistent to that determined by fuzzy TOPSIS. To some extent, it could be concluded that fuzzy TOPSIS can accurately determine the sustainability order when knowing the relative importance of the criteria for sustainability. However, LNG was recognized as the most sustainable alternative marine fuel by Deniz and Zincir (2016), and it is followed by hydrogen, and methanol. There are several reasons: (1) the criteria systems for sustainability assessment of the alternative marine fuels are different; (2) the results of this study are based on group meetings, three groups of decision-makers/stakeholders participated in the sustainability assessment, and different stakeholders have different opinions; and (3) weights of the criteria for sustainability assessment are different, and the final results highly depend on the weights of the criteria.

Table 19: The final results of WSM for ranking the three alternative marine fuels

	Methanol	LNG	Hydrogen
Weighted sum	(0.3084 0.5662 0.9354)	(0.3793 0.6444 1.0543)	(0.3858 0.6761 1.0477)
Crisp values	0.5940	0.6806	0.6964
Ranking	3	2	1

The relative importance of the criteria for sustainability highly depends on the preferences and opinions of the decision-makers, and the weights of the criteria usually change when the decision-makers change (Ren and Sovaccol, 2015). Thus, sensitivity analysis has been carried out in this study by implementing the following cases.

Case 0: Weights determined by the fuzzy logarithmic least squares method (see Table 12).

Case 1: Equal weight. $\omega_1 = \omega_2 = \cdots = \omega_{11} = 0.1111$. The same weight (0.1111) was assigned to the eleven criteria.

Cases 2-12: A dominant weight 0.40 was set to a dominant criterion, and the other ten were assumed to be equal importance with a weight of 0.06. For instance in Case i (i=2,3,…,12), $\omega_{i-1} = 0.40$ $\omega_j = 0.06$ $\quad j = 1,2,\cdots,11, j \neq ?-1$. As for cases 2-12, the dominant weight was assigned to EN_1, EN_2, EN_3, EN_4, EC_1, EC_2, T_1, T_2, T_3, S_1, and S_2, respectively.

The results of sensitivity analysis were presented in Figure 3. It is apparent that the sustainability orders of the alternative marine fuels may be changed if the weights of the criteria have been changed. In other words, the sustainability order may also change when changing the weights of the criteria. Therefore, the accurate determination of the weights of the criteria is of vital importance for accurately determining the sustainability order.

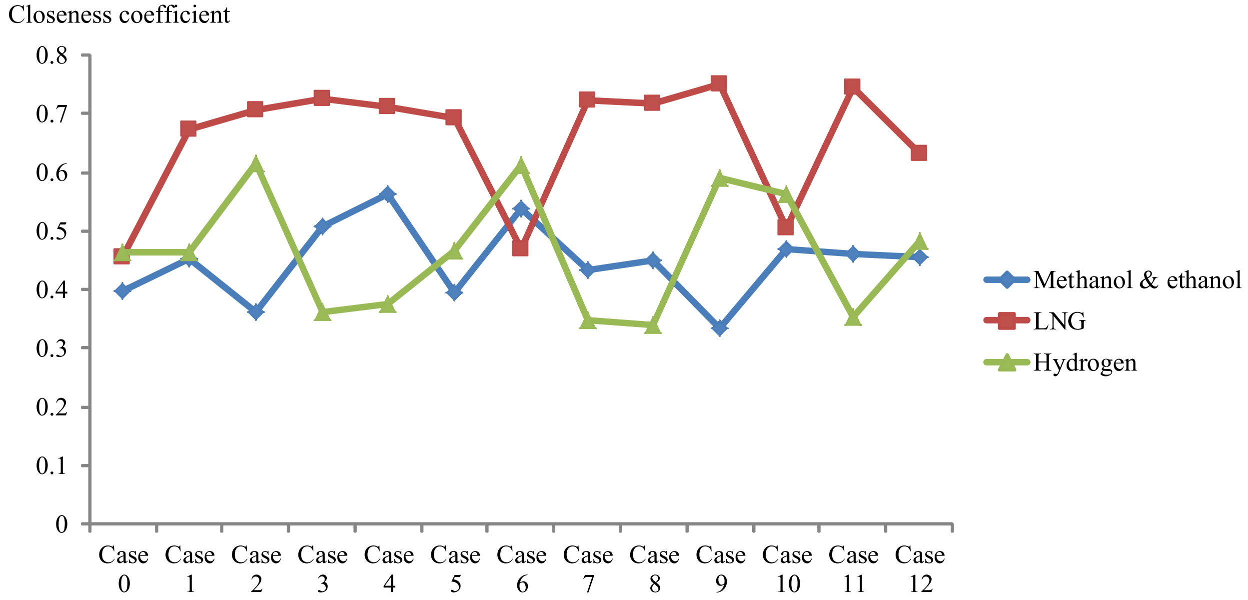

Figure 3: The results of sensitivity analysis

According to the results of sensitivity analysis, it is apparent that LNG was recognized as the most sustainable marine fuel among these three alternatives in most of the thirteen cases. However, hydrogen was recognized as the most sustainable in some cases when assigning bigger weights to the criteria in which hydrogen performs much better than the other two alternative marine fuels. For instance, hydrogen has been recognized as the most sustainable when using the weights determined by the fuzzy logarithmic least squares method (Case 0) to rank the three alternatives, because capital cost (EC_1) was recognized as the most important in this case, and hydrogen performs best in capital cost. This is not only the reason why hydrogen has been recognized as the most sustainable marine fuel among these three alternatives, but also the reason why the results in Case 0 are different from that determined in the work of Deniz and Zincir(2016).

4. Conclusions

The utilization of alternative marine fuels has been recognized as a promising way for achieving green shipping or low-carbon shipping. This study has developed a generic method for sustainability assessment of alternative marine fuels which can help the stakeholders/stakeholders to rank the sustainability order of various different marine fuels and determine the most sustainable marine fuel among multiple alternatives. A group multi-criteria decision making method was proposed for sustainability prioritization of alternative marine fuels. A criteria system for sustainability assessment of marine fuels which includes eleven criteria in environmental, economic, technological, and social aspects, namely CO_2 emission reduction, effect on NO_x emission reduction, effect on SO_x emission reduction, effect on PM emission reduction, capital cost, operational cost, maturity, reliability and capacity ,comply with emission regulations, and social acceptance, was firstly developed. Then, fuzzy logarithmic least squares method which allows the decision-makers to use linguistic variables to express their opinions was employed for determining the weights of the criteria for sustainability assessment of marine fuels. Finally, fuzzy TOPSIS which allows the decision-makers/stakeholders to use linguistic variables to depict the relative performances of the alternative marine fuels with respect to the criteria for sustainability assessment, was used to determine the sustainability order of the alternative marine fuels.

All in all, the proposed method for sustainability assessment of the alternative marine fuels has the following advantages:

(1) The opinions and preferences of multiple different groups of stakeholders can be all incorporated in the decision-making process;

(2) The participants can easily use linguistic variables to express their opinions and preferences when determining the relative importance of the criteria and describing the relative performances of the alternatives with respect to the evaluation criteria;

(3) The sustainability of the alternative marine fuels can be quantified even if the decision-makers/stakeholders do not know the exact data of the alternatives with respect to some of the criteria for sustainability assessment.

However, there is also a drawback which can be improved in future-all the data used in this study are based on human judgments, so the data of the alternative marine fuels with respect to some hard criteria cannot be fully used by the proposed method. Accordingly, the future work of the authors will focus on combing the multi-criteria decision making method based on crisp numbers and the fuzzy decision-making method based on the human judgments for sustainability assessment of alternative marine fuels.

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