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Selection of Sustainable Alternative Energy Source for Shipping: Multi-Criteria Decision Making Under Incomplete Information

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Abstract: The selection of alternative energy sources for shipping can effectively mitigate the problems of high energy consumption and severe environmental problems caused by shipping. However, it is usually difficult for decision makers to select the most sustainable alternative energy source for shipping among multiple alternatives due to the complexity of considering different aspects of performances and the lack of information. This study 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. According to the developed method, nuclear power has been recognized as the most sustainable alternative energy source for shipping, followed by liquefied natural gas (LNG) and wind power, and sensitivity analysis reveals that the weights of the criteria have significant on the sustainability sequence of the three alternative energy sources for shipping. The developed method can be popularized for selecting the most sustainable alternative energy source despite incomplete information.

Keywords: Shipping; Alternative energy source; Dempster-Shafer theory; Fuzzy analytic hierarchy process; Decision-making

1. Introduction

Because of shipping's ability to move large quantities of cargo with high efficiency and low transportation cost, it plays a dominant role in world trade, and there is no doubt that shipping is very important for the global economic development. However, it also causes numerous environmental problems. The dominant emissions from ships, which include SO_x , NO_x, CO_2, and particulate matter (PM) [1-3], have a significantly negative impact on air quality. It was estimated that the emissions from a ship using the fuel with 3.5% sulphur accounts to that emitted 210,000 trucks [4].

To reduce atmospheric emissions from seagoing ships, various regulations for emission control of ships have been drafted. The International Maritime Organization (IMO) has taken various actions to regulate air pollution from ships. One of the most important regulations is MARPOL Annex VI, which was first adopted in 1997 to prevent air pollution from shipping [5]. In addition to national and international strategies and regulations, technical measures for SO_x, NO_x, or greenhouse gas reduction from shipping, including technologies for emission reduction (i.e., low-sulphur fuel [6], scrubbers, and LNG [7]), are also widely discussed and studied. Among these technical measures, different alternative low-carbon energy sources, such as LNG, nuclear power, biodiesel, and wind power for the propulsion of ships, have been considered as possible pathways for mitigating the high energy consumption and severe environmental problems of shipping. For instance, it is estimated that the application of LNG on a 33,000 DWT tanker can contribute to a reduction of 35% of the operational costs and 25% of the CO_2

emissions [8]. Moreover, the use of LNG can reduce approximately 80-85% of NO_x emissions and almost all SO_x emissions compared with heavy fuel oil [9]. Accordingly, the use of alternative energy sources for the propulsion of ships has been a hot topic of discussion to achieve greener and more environmentally friendly shipping.

Different alternative energy sources have different economic, environmental and social performances; one alternative energy source may perform better than another energy sources in one aspect but may perform worse in another. Accordingly, decision makers are usually puzzled when choosing a suitable alternative energy source for shipping, as the selection is usually a process involving identifying multiple criteria and evaluating multiple alternatives [10]. Thus, developing a multi-criteria decision support framework for helping the decision-makers to select the most suitable alternative energy source according to their preferences and the actual conditions is of vital importance.

The previous MCDM methods for selecting the alternative energy sources for shipping has the following weak points according to literature reviews [11-16]: (i) the lack of the methods for multi-criteria decision making under incomplete information; (ii) the lack of the methods for addressing the vagueness, ambiguity and uncertainties existed in human judgments; (iii) the lack of the complete criteria system for sustainability assessment of alternative energy sources for shipping. This study has developed a method to fill these research gaps. Accordingly, the novelties of this study is to develop a multi-criteria decision making method by combining DS theory and the trapezoidal fuzzy analytic hierarchy process (TFAHP) that can address the problem of incomplete information and allows the users to use linguistic terms to express their opinions on the relative importance of the criteria for selecting the most sustainable alternative energy sources for shipping.

2. Literature review of MCDM methods

The selection of the most suitable alternative energy source can be described as a multi-criteria decision-making (MCDM) problem, where methods that can characterize a finite set of alternatives and compare their relative priorities are used [17]. There are various MCDM methods that have been used within the energy field, i.e., TOPSIS (technique for order preference by similarity to ideal solution) [18], PROMETHEE (preference ranking organization method for enrichment and evaluations) [19], the VIKOR (Viekriterijumsko Kompromisno Rangiranje) method [20-21], DEA (data envelopment analysis) [22], the ELECTRE (elimination and choice translating reality) method [23], and additional extensions of these methods by combining them with fuzzy theory or grey theory [24-25]. There are also various methods for determining the weights of the criteria that represent both their relative importance in decision-making and the preferences of the decision-makers; these methods can be categorized into three types: (1) the objective methods which can determine the weights of the criteria based on the data of the alternatives with respect to each criterion, i.e., the entropy method and criteria importance through inter-criteria correlation (CRITIC) method; (2) the subjective methods which determine the weights of the criteria based on the preferences and willingness of the decision-makers, i.e., the analytic hierarchy process (AHP) which can determine the weights of the criteria by constructing the comparison matrix and Delphi method which can determine the weights of the criteria through the survey of the opinions of the decision-makers ; (3) the combined methods, which combine both the subjective and objective methods [26-27].

However, these methods cannot be used directly for alternative energy source selection for shipping, as this selection type usually faces severe uncertainty problems, including aleatory and epistemic types [28]. Epistemic uncertainty is the most severe problem in the selection of alternative energy sources for shipping, as people cannot make accurate judgments due to the lack of information. Based on the above-mentioned literature, developing an innovative methodology to be used in situations with incomplete information is of vital importance for decision makers.

3. Criteria for sustainability assessment of alternative energy sources

The concept of sustainable development can be interpreted in many different ways. Othman et al. [29] noted that it aims to simultaneously achieve economic prosperity, environmental health, and social responsibility. Accordingly, the criteria used for sustainability assessment are defined within the three pillars of sustainability: the economic performances, the environmental impacts, and the social effects. Jiménez-González and Woodley [30] hold the view that analysing and comparing sustainability will require a comprehensive assessment that balances these three different spheres of sustainability (see Figure 1) and that this can only be achieved through a multi-variable optimization.

However, there is no common standard for establishing an evaluation criterion system for sustainability assessment and analysis; Musango *et al*. [31] have noted that data limitations are often a significant obstacle to generate large indicator sets. Data limitations consist of two parts: uncertainties [32-33] and incompletion [34-35]. Uncertainties refer to the variations associated with physical systems and/or the environment, whereas incompletion refers to the lack of knowledge and/or information. In addition to the difficulties caused by uncertainties and incompletion, the repeatability and relevancy in the criteria system are difficult to establish [36]. To solve this problem, Wang et al. [36] and Ye et al. [37] suggested five principles of selecting the "major" criteria: (1) the systemic principle, (2) the consistency principle, (3) the independency principle, (4) the measurability principle, and (5) the comparability principle. In addition to these five principles, we also hold the view that the 'significance principle' (6) defined in the present study, which refers to the selection criteria for sustainability assessment, should contribute to distinguishing the priorities of different alternative energy sources for shipping.

In addition, the metrics for sustainability assessment have been widely used for the selection of energy alternatives as they can completely evaluate the integrated performances of the alternatives in various aspects, i.e., the economic, environmental and social aspects. Ren et al. [38] noted that criteria within the technological area usually have significant effects on the economic and environmental aspects. Therefore, criteria in the technological aspect are usually incorporated in a sustainability assessment. Similarly, criteria within the political area have significant impacts on the economic, environmental, social, and technological aspects. For instance, regulations drafted by administrations that reflect the attitudes of the governments can significantly influence economic development, environmental protection, social satisfaction, and the advancement of technologies. Therefore, besides the main three pillars of sustainability (economic, environmental and social aspects), technological and political dimensions are also usually incorporated in a sustainability assessment. The present study uses four dimensions, namely, the technological, economic, environmental, and social-political aspects, to measure sustainability (see Figure 2).

For the sustainability assessment of alternative energy sources for shipping, 15 criteria in the four aspects are defined (see Table 1). There are three criteria in the technological aspect, including maturity, reliability, and energy storage efficiency; the economic aspect consists of infrastructure, capital cost, bunker price, repair and maintenance cost, training cost and crew wage; SO_x reduction, NO_x reduction, GHG emissions reduction, and PM reduction are the four criteria belonging to the environmental aspect; and finally, social acceptability, governmental support, and safety are the three criteria of the social-political aspect.

The alternative energy sources within shipping primarily refer to liquefied natural gas (LNG), nuclear power, wind power, solar power, biofuels, and hydrogen, and the stakeholders usually consider the above-mentioned criteria to select the most suitable option when facing multiple alternative energy sources. These criteria are specified as follows:

(1) Technological aspect

● Maturity

Borrowing the concept of technology maturity from Ref. [39], the maturity in this study can be defined as a measure of the degree of maturity of the technology related to each of the alternative energy sources, which refers to how widespread and proficiently each technology can be used for shipping. For instance, the maturities of liquefied natural gas (LNG) and wind power as two alternative energy sources for the propulsion are different. LNG, which is usually used in marine boiler or dual fuel engines, has served as a marine fuel for approximately 50 years, though it has primarily been limited to LNG vaporization (boil-off) from cargo tanks until 2000 [40], whereas wind power used as propulsion power within commercial shipping is seldom considered even though it is not an emerging alternative energy source [41]. However, using wind power might be worth considering, as it is both cost and emission free; unfortunately, none of the present designs of sails, rotors or kites can completely replace ship engines but can only be a supplement.

● Reliability

Reliability is a criterion to measure the resistance and robustness of the alternative energy source to changes of external conditions, as well as the independence of external conditions [42]. For instance, wind and solar power are two clean alternative energy sources for shipping, but they are highly dependent on the weather. Thus, the propulsion of ships powered by wind and solar energy is significantly influenced by external factors, and these two alternative energy sources thereby have low reliability if they are considered as the only power source installed in the vessel.

● Energy storage efficiency

The energy storage efficiency criterion is measured by the fuel power density and the refuel frequency. The fuel power density represents the power that can be released per unit fuel, and the refuel frequency indicates the required time for refuelling of the ships on a given route [43]. The fuel power density is used to measure the utilization efficiency of space; low fuel power density will lead to a large space requirement for a bunker, which further causes the reduction of space. High refuel frequency will lead to the increase of voyage time, detours, and operational costs [43]. For instance, the fuel power density of LNG is low (a factor of ~2.5) compared with oil fuels; this will require consideration of either reducing the cargo capacity or having a high refuel frequency [44-45].

(2) Economic aspect

● Infrastructure

The infrastructure refers to the supporting facilities for establishing alternative energy sources as marine fuels for the propulsion of ships. For instance, the infrastructure for using LNG consists of distribution pipelines, liquefaction plants and bulk storage facilities [44]. The completion of the supporting infrastructure is used to measure the feasibility of using the alternative energy sources for the propulsion of ships at a large scale.

● Capital cost

Changing the type of energy source requires retrofitting an existing ship or building a new ship [43]. The capital cost regarding each alternative energy source refers to the total costs for shipbuilding or the retrofitting of the old ship to adopt the new alternative energy source. As an example, the initial investment of a new vessel equipped with LNG propulsion will increase 10%-50% according to the prediction of DNV [46].

● Bunker price

The bunker price refers to the price of an alternative energy source used for ship propulsion. The bunker price is quite important for the stakeholders, as it normally represents a large portion of the total costs; in some cases of heavy fuel oil, the bunker price accounts for approximately 60% of the total operational cost [43]. Some alternative energy sources are more expensive than heavy oil fuels, e.g., low-sulphur fuel, as the cost of refining the fuel and converting it into low-sulphur fuel is a significant cost for the oil company [46].

●Repair and maintenance cost

The adoption of alternative energy sources requires the instalment of facilities and infrastructure for supporting the utilization of the alternative energy source. The repair and maintenance cost represents the cost for repair and maintenance of these facilities and infrastructure [43].

● Training cost and crew wage

The training cost and crew wage represents the cost for training and education of operators and crew to operate the ship using the alternative energy source. For instance, adopting a new energy source (e.g., nuclear, wind power, and solar power) requires a crew with special professional skills; these crews might require higher wages than crews operating ships using the usual crude oil for propulsion [43].

(3) Environmental aspect

●SO_x reduction

SO_x emissions refer to sulphur dioxide (SO_2) and sulphur trioxide (SO_3) that can lead to acid rain and also have a significant negative impact on vegetation, human health and buildings [47]. The shipping industry is one of the top emitters of SOx among many industries, and it was estimated that 2.3 million tons of SO_2 was emitted by ships in the seas surrounding Europe in 2000 [48]. The alternative energy sources with low or without sulphur can significantly reduce SO_x emissions.

● NO_x reduction:

NO_x emissions refer to nitrogen monoxide (NO) and nitrogen dioxide (NO_2) emissions that can cause acid rain and lead to over-fertilization and smog formation [47]. The traditional bunker oil used in ships can lead to NOx emissions, which far exceed those from normal diesel; NO_x emissions from shipping accounts for 15%-17% of global NO_x emissions [46, 49].

● GHG reduction:

Greenhouse Gas (GHG) emissions mainly refer to carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), and perfluorooctane sulphonate (PFCs), which all contribute to global warming [8]. However, the contributions of these emissions vary; CO_2 contributes the most, as 1050 million tonnes were emitted from global shipping in 2007, followed by CH_4, N_2O, and HFCs. The annual amount of these latter three emission accounts for approximately 21 million tons of CO_2 equivalents; the contribution of the other GHG gases are negligible [46].

●PM reduction

Particulate matter (PM) is related to poor-quality marine fuel. Particles are produced during the combustion process and mainly occur in the form of soot and ash [49]. PM has a significant impact on the air quality. For instance, the severe smog in China is caused by PM2.5. It is estimated that, globally, 1.7 million tonnes of PM were released in 2007 by ships, which is 1.5 times that in 1997 [46]. Controlling PM emissions in shipping has significant merit for improving air quality.

(4) Social-political aspect

●Social acceptability

Social acceptability expresses the overview of the opinions related to the adoption of the alternative energy source [39]; it is used to measure the attitudes of the public to the adoption of a particular alternative energy source for shipping activities.

● Governmental support

This criterion is a measurement for how the adoption of alternative energy sources for shipping can fulfil the regulation standards and policies drafted by government administrations [39].

● Safety:

Safety refers to the safety of ship operation and living and working on board and the safety of the ports and the citizens that live around the ports [43]. Safety is one of the most important criteria to judge the performance of alternative energy sources, as low risks to people is the first prerequisite for using an alternative energy source.

It is worth noting that users should choose the most suitable criteria for sustainability assessment according to the actual conditions, and thus, they can choose the most suitable criteria among these 15 criteria when conducting sustainability assessment of alternative energy sources before decision-making. Moreover, the decision-makers can also add other criteria (i.e. decommissioning cost and solid wastes) for sustainability assessment of the alternative energy sources for shipping according to the actual conditions and their preferences.

4. Method

In this section the DS/TFAHP based multi-criteria decision-making method for sustainability assessment of technologies for emission reduction for shipping is presented. First, the DS theory is introduced; then, the TFAHP method is presented. Finally, a method for multi-criteria decision-making under conditions of incomplete information is proposed by combining DS theory and FAHP.

4.1 Dempster-Shafer (DS) theory

The Dempster-Shafer theory of evidence developed by Dempster and Shafer is a technique in which the basic probability of an alternative decision can be evaluated, even when the decision matrix is incomplete [50]. The Dempster-Shafer (DS) theory, which is a numerical method for evidential reasoning that can describe uncertainty caused by both randomicity and incomplete information [11], has therefore been employed in this particular study. The DS theory has been specified in Ref. [51-52], this theory has been widely used in combination with other multi-criteria decision making methods [53]. For instance, the DS/AHP method which is the combination of DS theory and AHP can effective can handle the problem with ambiguous information and cognitive limitations; however, AHP method cannot solve the vagueness and ambiguity existed in human judgments.

Let $\Theta = \{h_1, h_2, ..., h_n\}$ be a finite set of n hypotheses (frame of discernment). A basic probability assignment (bpa) is a function m: $2^{\Theta} \to [0,1]$ such that,

$$m(\varnothing) = 0 \text{ and } \sum_{x \in 2^{\Theta}} m(x) = 1 \quad (1)$$

where $\varnothing$ represents the empty set, x is any set of Θ, m() represents the probability assignment function, and 2^{Θ} is the power set of Θ, which consists of all of the subsets of Θ, i.e.,

$$2^{\Theta} = \{\varnothing, \{h_1\}, ..., \{h_n\}, \{h_1, h_2\}, ..., \{h_1, h_n\}, ..., \Theta\} \quad (2)$$

Any subset of x in the frame of discernment Θ for which m(x) is non-zero is called a focal element and represents the exact belief in the proposition depicted by x. The assigned probability of Θ (namely, $m(\Theta)$) is called the degree of ignorance, and it represents the amount of uncertainty within the bpa of m(x).

A belief measure is a function Bel: $2^{\Theta} \to [0,1]$ and is drawn from the sum of the probabilities that are subsets of the probabilities in question, defined as

$$Bel(A) = \sum_{B \subseteq A} m(B) \; for\, all\; A \subseteq \Theta \quad (3)$$

The belief measure represents the confidence that a proposition y lies in A or any subset of A.

A plausibility measure is a function Pls: $2^{\Theta} \rightarrow [0,1]$, defined as

$$Pls(A) = 1 - Bel(\overline{A}) = \sum_{A \cap B \neq \varnothing} m(B) \; for\, all\, A \subseteq \Theta \tag{4}$$

where $\overline{A}$ denotes the complement of A.

The plausibility measure (Pls) represents the possible support that a proposition y lies in A. Bel and Pls represent the exact support and possible support to A, respectively. Therefore, $\left[Bel\left(A\right), Pls(A\right]$ is an interval of support and can be observed as the lower and upper bounds of the probability to which A is supported.

Dempster's rule can be used to combine the evidence from different sources, as shown in Eq.5, and this rule assumes that these sources are independent.

$$m = m_1 \oplus m_2 \oplus \ldots \oplus m_K \tag{5}$$

In the above equation, $\oplus$ represents the operator of combination.

For the two belief structures m1 and m2, the combination $m_1 \oplus m_2$ is defined by

$$\left[m_1 \oplus m_2\right]\left(x\right) = \begin{cases} 0, y = \varnothing \\ \dfrac{\sum_{s_1 \cap s_2 = x} m_1(s_1) m_2(s_2)}{1 - \sum_{s_1 \cap s_2 = \varnothing} m_1(s_1) m_2(s_2)} \end{cases} \tag{6}$$

where A and B are both focal elements and $\left[m_1 \oplus m_2\right]\left(x\right)$ represents a bpa.

Dempster's rule is both commutative and associative [52], as shown in Eq. 7 and Eq. 8, respectively:

$$m_1 \oplus m_2 = m_2 \oplus m_1 \tag{7}$$

$$(m_1 \oplus m_2) \oplus m_3 = m_1 \oplus (m_2 \oplus m_3) \tag{8}$$

4.2 Fuzzy Analytic Hierarchy Process

The analytic hierarchy process (AHP), which is the most popular method for determining weights of criteria, sometimes does not perform well, as human judgments usually involve subjectivity, vagueness and ambiguity [12]. It can also be difficult for decision-makers to use traditional AHP, which employs a nine-point scale (1-9) to depict the relative priority between two objects for accurately determining the relative importance of the criteria for sustainability assessment. However, fuzzy set theory which can appropriately express the opinions of the decision-makers has the ability to address this. Accordingly, various extended AHP methods, such as a combination of the AHP and fuzzy set theory, so-called "fuzzy AHP", have been widely used in energy engineering, i.e. prioritization of measures for energy security enhancement[12], performance evaluation of a V down perforated baffle roughened rectangular channel [13], prioritization of strategic measures for promoting shale gas industry [14], power substation location selection [15], and prioritization of low-carbon energy sources for energy security enhancement [16]. However, the fuzzy AHP method cannot handle the problem with incomplete information. In other words, fuzzy AHP cannot effectively achieve multi-criteria decision making when some information for decision-making is incomplete.

In this section, we first introduce the fuzzy set theory, followed by a description of the trapezoidal fuzzy analytic hierarchy process, which uses fuzzy numbers to establish a comparison matrix for determining the weights of the criteria.

4.2.1 Fuzzy set theory

A fuzzy set $\tilde{a}$ is in a universe of discourse X that is characterized by a membership function $\mu_{\tilde{a}}(x)$, which associates with each element x in X, a real number in the interval [0, 1], and the function value represents the grade of membership of x in $\tilde{a}$ [54]. Accordingly, the membership function $\mu_{\tilde{a}}(x)$ of the trapezoidal fuzzy number $\tilde{a} = \left(a_1, a_2, a_3, a_4\right)$ is defined to map each element x in X (a universe of discourse) to a real number in the interval [0, 1]. The concept of trapezoidal fuzzy number [55-56] can be formulated as in Eq. 9 and is illustrated in Figure 3.

$$\mu_{\tilde{a}}(x) = \begin{cases} \dfrac{x - a_1}{a_2 - a_1} & a_1 \le x \le a_2 \\ 1 & a_2 \le x \le a_3 \\ \dfrac{a_4 - x}{a_4 - a_3} & a_3 \le x \le a_4 \end{cases} \tag{9}$$

Here a_1, a_2, a_3 and a_4 are membership function parameters.

The operation laws for the trapezoidal fuzzy numbers and the fuzzy set are summarized in Table 2 [56-57].

4.2.2 Trapezoidal Fuzzy Analytic Hierarchy Process

The trapezoidal fuzzy analytic hierarchy process is specified in the following four steps [58-59]:

Step 1: Comparison matrix determination: Establishing the pair-wise comparison matrix by using the trapezoidal fuzzy numbers.

Assume that there are a total of N factors (i=1,2,…, N) with the i-th criterion denoted by C_i. A pair-wise comparison matrix can be established by decision-makers by using the fuzzy scales presented in Table 3 [59-60]. Each element in the comparison matrix can be obtained by comparing the relative priority of each pair of factors, as shown in Eqs. 20 and 21:

$$\tilde{A}=\begin{vmatrix}(1,1,1,1) & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & (1,1,1,1) & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{n1} & 1/\tilde{a}_{2n} & \cdots & (1,1,1,1)\end{vmatrix} \tag{20}$$

$$\tilde{a}_{ji}=\frac{1}{\tilde{a}_{ji}}=\left(\frac{1}{a_{ij}^{4}},\frac{1}{a_{ij}^{3}},\frac{1}{a_{ij}^{2}},\frac{1}{a_{ij}^{1}}\right) \tag{21}$$

where $\tilde{A}$ is the comparison matrix composed of trapezoidal fuzzy numbers, and $\tilde{a}_{ij}=\left(a_{ij}^{1},a_{ij}^{2},a_{ij}^{3},a_{ij}^{4}\right)$ is a trapezoidal fuzzy number that represents the relative importance of C_i compared with C_j.

In contrast to the traditional AHP that employs a scale from 1 to 9 to compare the relative priority between each pair of criteria, the TFAHP employs trapezoidal fuzzy numbers, which will be more accurate for expressing the preferences of the decision-makers because human judgments are usually vague, subjective and ambiguous.

Step 2: Defuzzification: Defuzzifying the comparison matrix composed of trapezoidal fuzzy numbers and consistency checking.

The comparison matrix determined in Step 1 composed of trapezoidal fuzzy numbers can be defuzzified according to Eq. 23. Accordingly, the defuzzified matrix can be obtained according to Eqs.22-23:

$$A = \begin{vmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{vmatrix} \tag{22}$$

$$a_{ij} = \frac{a_{ij}^1 + 2a_{ij}^2 + 2a_{ij}^3 + a_{ij}^4}{6} \tag{23}$$

where A is the comparison matrix composed of crisp numbers, and a_{ij} is the defuzzified values of $\tilde{a}_{ij} = \left(a_{ij}^1, a_{ij}^2, a_{ij}^3, a_{ij}^4\right)$, which represents the relative importance of C_i compared with C_j.

According to the comparison matrix A, the principal eigenvector of this comparison matrix can be obtained by Eq. 24:

$$AW = \lambda_{\max} W \tag{24}$$

where W is the maximal eigenvector of matrix A, and $\lambda_{\max}$ is the corresponding eigenvalue.

A consistency ratio can be obtained according to Eq. 25 to judge whether the comparison matrix A is consistent or not.

$$CR = \frac{\lambda_{\max} - n}{(n-1)RI} \tag{25}$$

Here, CR is the consistency ratio, $\lambda_{\max}$ is the maximal eigenvalue of the comparison matrix, and RI is the average random index with the same dimension as A, which can be determined according to Table 4 [61].

The matrix can be regarded as acceptable if CR<0.1. The matrix A is acceptable if the matrix $\tilde{A}$ is acceptable; otherwise $\tilde{A}$ must be modified until it becomes acceptable.

Step 3: Fuzzy weight determination: Calculating the fuzzy weights.

The fuzzy geometric mean can be calculated according to the geometric mean technique derived from Buckley [62], according to Eqs. 26-30:

$$\tilde{r}_i = \left(\tilde{a}_{i1} \times \tilde{a}_{i2} \cdots \times \tilde{a}_{iN}\right)^{1/n} = \left(r_i^1, r_i^2, r_i^3, r_i^4\right) \quad (26)$$

$$r_i^1 = \prod_{j=1}^{N} a_{ij}^1 \quad (27)$$

$$r_i^2 = \prod_{j=1}^{N} a_{ij}^2 \quad (28)$$

$$r_i^1 = \prod_{j=1}^{N} a_{ij}^3 \quad (29)$$

$$r_i^1 = \prod_{j=1}^{N} a_{ij}^4 \quad (30)$$

Then, the fuzzy weight of each factor can be obtained by Eqs. 31-35:

$$\tilde{\omega}_i = \tilde{r}_i \times \left(\tilde{r}_1 + \tilde{r}_2 + \cdots + \tilde{r}_N\right)^{-1} = \left(\omega_i^1, \omega_i^2 . \omega_i^3, \omega_i^4\right) \quad (31)$$

$$\omega_i^1 = r_i^1 \left(\sum_{i=1}^{N} r_i^4\right)^{-1} \quad (32)$$

$$\omega_i^2 = r_i^2 \left(\sum_{i=1}^{N} r_i^3\right)^{-1} \quad (33)$$

$$\omega_i^3 = r_i^3 \left(\sum_{i=1}^{N} r_i^2\right)^{-1} \quad (34)$$

$$\omega_i^4 = r_i^4 \left(\sum_{i=1}^{N} r_i^1\right)^{-1} \quad (35)$$

where $\tilde{r}_i$ is the geometric mean of the fuzzy comparison values of the *i*-th factor of each of the other criteria, and $\tilde{\omega}_i$ represents the fuzzy weight of the *j*-th factor.

Step 4: Crisp weight determination: Transforming the fuzzy weights into crisp numbers.

In this step, the fuzzy weight of each factor is defuzzified according to Eq. 36:

$$\omega_i' = \frac{\omega_i^1 + 2\omega_i^2 + 2\omega_i^3 + \omega_i^4}{6} \tag{36}$$

where ω_i' represents the crisp weight of the *j*-th factor, and ω_i^1, ω_i^2, ω_i^3 and ω_i^4 are the elements of the fuzzy weight, $\tilde{\omega}_i = \left(\omega_i^1, \omega_i^2 . \omega_i^3, \omega_i^4\right)$.

The crisp weight of each factor can be normalized to obtain the normalized weight,

$$\omega_j = \omega_j' \Big/ \sum_{j=1}^{n} \omega_j' \tag{37}$$

$$W = \left[\omega_1, \omega_2, \cdots, \omega_n\right] \tag{38}$$

where ω_j is the normalized weight of the *j*-th factor, and W is the weight vector.

4.3 Multi-criteria decision making for selecting the best alternative

Decision making under the conditions of incomplete information means to make a decision with incompleteness in preference information on alternatives (criteria). The multi-criteria decision-making method for decision-making under uncertainties by combining FAHP and DS theory was developed, and this method can be described by the following seven steps:

Step 1: Calculating the weights of the criteria using the FAHP method.

In this step, the FAHP method is used to determine the weights of the criteria (the criteria for multi-criteria decision making). First, the weights of the aspects (i.e., the criteria for multi-criteria decision making) are categorized into several aspects (i.e., economic, environmental and social-political aspects); then, the weights of the criteria in each aspect are calculated; finally, the global weights of the criteria are computed.

Step 2: Establishing the hierarchical structure of the decision-making.

In the hierarchical structure of the decision making, the first level is selecting the best alternative under conditions of incomplete information, the second level is the criteria for decision making, and the third level is the focal elements identified from the decision-making matrix. The focal elements can be determined by the stakeholder/decision-makers according to the obtained information and their own knowledge.

Step 3: Calculating the values of bpa of all of the focal elements of each criterion.

Assume that there are d_j focal elements $s_{1j}, s_{2j}, \ldots, s_{dj}$ identified in the i-th criterion and that the basic probability assignment of the i-th focal element under the j-th criterion can be calculated using Eqs. 39-40 [63-64]. $m_j(\Theta)$ is used as a measure of the degree of ignorance of the judgments with respect to the j-th criterion.

$$m_j(s_{ij}) = \frac{p_{ij}\omega_j}{\sum_{1}^{d_j} p_{ij}\omega_j + \sqrt{d_j}}, i = 1,2,\ldots,d_j \; and \; s_{ij} \neq \Theta \tag{39}$$

$$m_j(\Theta) = \frac{\sqrt{d_j}}{\sum_{1}^{d_j} p_{ij}\omega_j + \sqrt{d_j}} \tag{40}$$

In the above equations, ω_j represents the weight of the j-th criterion, p_{ij} represents the preference scale value of the i-th focal element (s_{ij}) under the j-th criterion, and $m_j(s_{ij})$ and $m_j(\Theta)$ are the bpa values of s_{ij} and Θ, respectively.

The preference scale values can be obtained according to the performances of the alternatives and the experience of the decision-makers; a five-scale method proposed by Ref. [65] is used in this study, as presented in Table 5. The verbal statement associated with the scale values ranging from 'moderately preferred' (scale value 2) up to 'extremely preferred' (scale value 6) can be used by decision makers to assess their preference of the focal elements compared to the frame of discernment Θ. It is worth pointing out that there usually are multiple decision-making participating in the decision-making and different decision-makers may have different opinions. In order to address this, the method for achieving consensus provided in Ref. [24] could be used to achieve a final consensus.

Step 4: Data fusion by Dempster's rule.

The combined bpa values are calculated according to Eq. 6-8.

Step 5: Calculating the belief and plausibility measures.

The belief and plausibility measures of the focal elements are calculated according to Eq. 3 and Eq. 4.

Step 6: Calculating the degree of preference.

The degree of preference of i-th alternative over the j-th alternative, denoted $P_{ij} \in [0,1]$, is defined as follows [1]:

$$P_{ij} = \frac{\max\{0, Pls(i) - Bel(j)\} - \max\{0, Bel(i) - Pls(j)\}}{\{Pls(i) - Bel(\mathrm{i})\} + \{Pls(j) - Bel(j)\}} \tag{41}$$

Step 7: Ranking the alternatives.

The following principals can be used for ranking the alternatives [50, 66]:

(1) The i-th alternative is superior to the j alternative only if $P_{ij} > 0.5$;

(2) The i-th alternative is indifferent to the j-th alternative only if $P_{ij} = 0.5$;

(3) The i-th alternative is inferior to the j-th alternative only if $P_{ij} < 0.5$;

Then, the prior sequence of the alternatives can be ranked according to the rules in this step.

Step 8: Sensitivity analysis and validating the results.

The sensitivity analysis can be conducted by changing the weights of the criteria to investigate the bpa values of the focal elements under each criterion. In order to validate the results determine by the proposed MCDM method for decision-making under incompletion, some other MCDM methods can be used to validate the results.

The proposed multi-criteria decision making method has the following advantages:

(1) It can help stakeholders/decision makers select the most base alternative uncertainty and incomplete information. In other words, the proposed method can overcome difficulties, such as uncertainties and incomplete information, that usually exist in traditional multi-criteria decision-making processes.

(2) It allows the stakeholders/decision makers to use linguistic terms to express their opinions about the relative importance of criteria for multi-criteria decision making.

(3) It is an object-oriented method for decision making o. In other words, this method can incorporate the preference and willingness of stakeholders/decision makers and select the best alternative according to the preferences and willingness of the decision-makers/stakeholders as well as the actual conditions.

5. Case Study

To illustrate the proposed model, three representative technologies, namely, LNG which is a promising low-carbon fossil fuel for ship propulsion, nuclear which is atomic power that has high potential to be widely used for ship propulsion, and wind power which is a low-carbon renewable energy source for ship propulsion are analysed. The illustration of the proposed model through the case study of these three representative alternative energy sources is to assure that the proposed method is a generic methodology and can be popularized to other cases under different conditions.

(1) LNG (A_1): A marine LNG engine is a dual fuel engine that uses natural gas and bunker fuel to convert chemical energy in to mechanical energy, and the natural gas is stored in liquid state (LNG) and the boil-off gas is routed to and burned in dual fuel engines [7]. Liquefied natural gas is used as the fuel for ship's propulsion. There are three types of LNG engines, as specified in Ref. [44]. One type is lean burn, spark-ignition, pure gas types operating on the Otto cycle and using a spark plug to ignite the gas/air mixture in the combustion chamber with a power range from 316 kW to 9,700 kW, another type is dual fuel with diesel pilot engines operating on the Otto cycle and using natural gas together with a second fuel source, and the power ranges from 720 kW to 17,500 kW, and the other type is direct injection with diesel pilot engines, and the current power of slow-speed engines can reach 42, 700 kW [44].

(2) Nuclear power (A_2): Nuclear power generation is the fission of large, heavy nuclei into smaller fission products under controlled chain reactions, thereby releasing a large amount of heat energy, which is transferred to a coolant to generate useable power via an appropriate thermodynamic cycle [67]. A submarine nuclear

reactor's power is much smaller than the land based reactors, and its reactor power is in the range of the hundreds of MWs, 10 MW in prototypes to 200 MW in large subsurface vessels, and 300 MW in surface ships [68].

(3) Wind power (A_3): Wind can provide energy to ships through Flettner rotors, kites or spinnakers, soft sails, wing sails and wind turbines [67]. Wind power usually works as a supplement to ship engines, rather completely replacing it as the power which is highly dependent on the wind speed is usually in the range of several MWs. For instance, it was reported that the latest SkySails product generation has a propulsion power of more than 2 MW [69].

The generic evaluation criterion system for sustainability assessment of the alternative energy sources for shipping was established in Section 2. However, the criteria for sustainable assessment of these three alternatives also need to be screened. According to the systemic and consistent principles, all four aspects (i.e., the technological, economic, environmental and social-political aspects) should be considered in the sustainability assessment of alternative energy sources. According to the independence principle, the criterion regarding PM reduction was deleted, as it is correlated to SOx reduction and a decrease in SOx emissions will lead to the reduction of PM emissions [46,70]. According to the measurability principle, the repair and maintenance cost and the training cost and crew wages were deleted, as we lacked information about both criteria. According to the significance principle, SOx reduction and governmental support were eliminated, as there is almost no difference because each technology can completely remove SOx and receive abundant governmental support due to the advantages of cleanliness and mitigating dependence on fossil fuels. Therefore, 10 criteria in four aspects are used for sustainability assessment of alternative energy sources for shipping, namely, maturity, reliability, and energy storage efficiency (the technological aspect); infrastructure, capital cost, and bunker price (the economic aspect); NOx reduction and GHG emissions reduction (the environmental aspect); and social acceptability and safety (the social-political aspect). The conduction of the proposed framework for sustainability assessment of three alternative energy sources for emissions reduction from shipping was based on the opinions of the experts.

Step 1: Weights calculation.

Using the four macro-aspects as an example, a pair-wise comparison matrix using trapezoidal fuzzy numbers can be determined, as presented in Table 6; the numbers taken are according to Table 3. For instance, the 'technological aspect' is regarded to be weakly important compared to the 'economic aspect', which corresponds to the trapezoidal fuzzy number (2, 5/2, 7/2, 4) (see cell (1,2) of Table 1). The reciprocal of (2, 5/2, 7/2, 4), namely (1/4, 2/7, 2/5, 1/2), is put into cell (2,1) of Table 6. Similarly, the other elements of Table 6 are determined.

According to Eq. 19, the elements in Table 6 can be transformed into crisp numbers. It is worth noting that only elements that are fuzzy numbers shown in the table are transformed; the other elements can be determined according to the traditional AHP method. For instance, cell (1,2), namely, (2, 5/2, 7/2, 4), belongs to the fuzzy number set in Table 3, and thus, it can be transformed into a crisp number with a value of 3;

therefore, 3 is put into cell (1,2) of Table 7. Similarly, all of the other elements in the comparison matrix can be determined using crisp numbers. According to the traditional AHP method, the maximal eigenvalue of this comparison matrix (λ_{max}) is 4.0310, and the consistency ratio (CR) is 0.0115; this is less than 10%, so the comparison matrix is acceptable. Therefore, the comparison matrix with respect to the four aspects using trapezoidal fuzzy numbers is acceptable.

The fuzzy geometric mean with respect to each of the four aspects can be determined according to Eqs. 26-30. For instance, the fuzzy geometric mean with respect to the technological aspect can be calculated as follows:

$$\tilde{r}_T = \left((1,1,1,1) \times \left(2, \frac{5}{2}, \frac{7}{2}, 4 \right) \times \left(1, \frac{3}{2}, \frac{5}{2}, 3 \right) \times \left(3, \frac{7}{2}, \frac{9}{2}, 5 \right) \right)^{1/4}$$

$$r_T^1 = (1 \times 2 \times 1 \times 3)^{1/4} = 1.5615$$

$$r_T^2 = \left(1 \times \frac{5}{2} \times \frac{3}{2} \times \frac{7}{2} \right)^{1/4} = 1.9034$$

$$r_T^3 = \left(1 \times \frac{7}{2} \times \frac{5}{2} \times \frac{9}{2} \right)^{1/4} = 2.5050$$

$$r_T^4 = (1 \times 4 \times 3 \times 5)^{1/4} = 2.7832$$

Similarly, the fuzzy geometric mean with respect to the other three aspects can also be determined:

$$\tilde{r}_T = \left(r_T^1, r_T^2, r_T^3, r_T^4 \right) = (1.5615, 1.9034, 2.5050, 2.7832)$$

$$\tilde{r}_{EC} = \left(r_{EC}^1, r_{EC}^2, r_{EC}^3, r_{EC}^4 \right) = (0.5373, 0.6435, 0.9036, 1.1067)$$

$$\tilde{r}_{EN} = \left(r_{EN}^1, r_{EN}^2, r_{EN}^3, r_{EN}^4 \right) (0.9036, 1.1067, 1.5541, 1.8612)$$

$$\tilde{r}_{SP} = \left(r_{SP}^1, r_{SP}^2, r_{SP}^3, r_{SP}^4 \right) = (0.3593, 0.3992, 0.5254, 0.6389)$$

According to the fuzzy geometric mean with respect to each of the four aspects, the fuzzy weights of the four aspects can be determined by Eqs. 31-35. For instance, the weight of the technological aspect can be determined by the following:

$$\tilde{\omega}_T = \tilde{r}_T \times \left(\tilde{r}_T + \tilde{r}_{EC} + \tilde{r}_{EN} + \tilde{r}_{SP}\right)^{-1} = \left(\omega_T^1, \omega_T^2 . \omega_T^3, \omega_T^4\right)$$

$$\omega_T^1 = \frac{r_T^1}{r_T^4 + r_{EC}^4 + r_{CN}^4 + r_{SP}^4} = \frac{1.5615}{2.7832 + 1.1067 + 1.8612 + 0.6389} = 0.2449$$

$$\omega_T^2 = \frac{r_T^2}{r_T^3 + r_{EC}^3 + r_{CN}^3 + r_{SP}^3} = \frac{1.9024}{2.5050 + 0.9036 + 1.5541 + 0.5254} = 0.3468$$

$$\omega_T^3 = \frac{r_T^3}{r_T^2 + r_{EC}^2 + r_{CN}^2 + r_{SP}^2} = \frac{2.5050}{1.9034 + 0.6435 + 1.1067 + 0.3992} = 0.6181$$

$$\omega_T^4 = \frac{r_T^4}{r_T^1 + r_{EC}^1 + r_{CN}^1 + r_{SP}^1} = \frac{2.7832}{1.5615 + 0.5373 + 0.9036 + 0.3593} = 0.8270$$

Similarly, the weights of the other aspects can also be determined:

$$\tilde{\omega}_T = \left(0.2449, 0.3468, 0.6181, 0.8270\right)$$

$$\tilde{\omega}_{EC} = \left(0.0841, 0.1172, 0.2230, 0.3289\right)$$

$$\tilde{\omega}_{EN} = \left(0.1414, 0.2017, 0.3835, 0.5531\right)$$

$$\tilde{\omega}_{SP} = \left(0.0562, 0.0727, 0.1296, 0.1899\right)$$

According to Eq. 36, the fuzzy weight of the technological aspect can be defuzzified:

$$\omega_T^{'} = \frac{\omega_T^1 + 2\omega_T^2 + 2\omega_T^3 + \omega_T^4}{6} = \frac{0.2449 + 2 \times 0.3468 + 2 \times 0.6181 + 0.8270}{6} = 0.5003$$

Similarly, the fuzzy weight of the other aspects can also be determined:

$\omega_{EC}^{'} = 0.1822$, $\omega_{EN}^{'} = 0.3108$, and $\omega_{SP}^{'} = 0.1085$

Finally, the normalized weight of the four aspects can be determined by Eq. 37:

$$\omega_T = \frac{\omega_T^{'}}{\omega_T^{'} + \omega_{EC}^{'} + \omega_{EN}^{'} + \omega_{SP}^{'}} = \frac{0.5003}{0.5003 + 0.1822 + 0.3108 + 0.1085} = 0.4541$$

$\omega_{EC} = 0.1654$, $\omega_{EN} = 0.2821$, and $\omega_{SP} = 0.0985$

Therefore, the weights of the technological, economic, environmental, and social aspects are 0.4541, 0.1654, 0.2821, and 0.0985, respectively. The results are comparable with that determined by the traditional AHP, as shown in Table 7, and it is apparent that the technological aspect is regarded as the most important for selecting the alternative energy sources for shipping, followed by the environmental, the economic and the social-political aspects in descending order according to the results determined by both the TFAHP and the traditional AHP methods. However, fuzzy numbers are more suitable for depicting human judgments, as they usually involve vagueness, ambiguity and subjectivity. Accordingly, the results determined by trapezoidal fuzzy AHP are more accurate. Similarly, the local weights of the criteria of each aspect can also be determined, as presented in Tables 8-11.

The global weight of each criterion can be determined by calculating the product of the local weight of the criterion and the weight of the aspect to which it belongs. For instance, the global weight of the 'maturity' criterion of the technological aspect is the product of the local criteria of the technological aspect and the weight of the technological aspect, namely, 0.5248×0.4545=0.2383. Thus, the global weight of the 'maturity' criterion is 0.2383. Similarly, the global weights of the other criteria can also be determined, as presented in Table 12. The weights of the four aspects determined by TFAHP and AHP and those of the 10 criteria determined by TFAHP and AHP are presented in Figure 4 and 5. It is apparent that the weights determined by TFAHP and AHP are comparable, however, there is also a slight difference between the weights; the weights determined by the TFAHP can reflect the preferences of decision-makers and are more accurate than the traditional AHP. Therefore, the weights of the criteria determined by TFAHP are used to determine the sustainability sequence of the alternative energy sources for shipping in the present study.

It is worth pointing out that this study aims at proposing an object-oriented multi-criteria decision making framework for helping the decision-makers to select the most sustainable alternative energy sources for shipping among multiple scenarios according to their preferences and the actual conditions. Thus, the weights are determined by the trapezoidal fuzzy analytic hierarchy process based on the preferences of the decision-makers and the actual conditions. Accordingly, the weights of the criteria determined by different decision-makers may be different as different decision-makers have different preferences and willingness, and the relative importance of the criteria for sustainability assessment may also be different when the decision-makers are different.

Step 2: The hierarchical structure of the decision-making.

The DS model of selecting the most sustainable alternative energy source for shipping is shown in Figure 6. The focal elements under each criterion are determined according to published works and expert knowledge. For instance, there are two focal elements under the first criterion of maturity (C_1), namely, $s_{11} = \{A_1, A_2\}$ and $s_{21} = \{A_3\}$, as both of the technologies of using LNG and nuclear power for ship propulsion have been developed and demonstrated for many years; however, using the wind as an emerging technique is relatively immature compared with LNG and nuclear power [43]. Similarly, the focal elements under the other nine criteria can be determined.

Step 3: The values of bpa for all of the focal elements of each criterion

The preference scales of the focal elements of different criteria are needed for calculating the bpa values. The preference scale values of the focal elements under different criteria were determined according to Table 5, and the results are presented in Table 13. It is worth noting that the preference scale values of the focal elements under different criteria are determined based on information provided in literatures and the knowledge of the experts.

Using the focal elements of criterion T_1 as an example, the preference scale values of $s_{11} = \{A_1, A_2\}$ and $s_{21} = \{A_3\}$ are 4 and 2, respectively. This indicates that the relative preferences of these two focal elements determined by the decision-makers compared with the frame of discernment Θ are 'strongly preferred' (scale value 4) and 'moderately preferred' (scale value 2), respectively.

Then, the bpa values of the focal elements under C_1 can be obtained by Eqs.39-40:

$$m_1(s_{11}) = \frac{4 \times 0.2383}{4 \times 0.2383 + 2 \times 0.2383 + \sqrt{2}} = 0.3352$$

$$m_1(s_{21}) = \frac{2 \times 0.2383}{4 \times 0.2383 + 2 \times 0.2383 + \sqrt{2}} = 0.1676$$

$$m_1(\Theta) = \frac{\sqrt{2}}{4 \times 0.2383 + 2 \times 0.2383 + \sqrt{2}} = 0.4973$$

Similarly, the bpa values of the other focal elements of the other criteria can also be calculated, as shown in Table 14.

Step 4: Data fusion by Dempster's rule.

The intermediate results of the combination of the bpa values of $m_1()$ and $m_2()$ are shown in Table 15; the combination of the bpa values can be obtained by Eq. 6.

For illustration, the focal element $\{A_3\}$ in Table 15 is derived from the intersection of the focal elements $\{A_3\}$ and $\{A_3\}$ from $m_1()$ and $m_2()$, the intersection of $\{A_3\}$ and Θ from $m_1()$ and $m_2()$, and the intersection of Θ and $\{A_3\}$ from $m_1()$ and $m_2()$, respectively. Its associate pre-bpa value was obtained by the multiplication of the respective bpa values, namely,

$$m_1(\mathrm{A}_3)\times m_2(\mathrm{A}_3)+m_1(\mathrm{A}_3)\times m_2(\Theta)+m_1(\Theta)\times m_2(\mathrm{A}_3)$$
$$=0.0195+0.0994+0.0578=0.1767$$

The sum of the products of the bpa values associated with the empty intersection ($\varnothing$) of the focal elements is 0.0877. This value is included in the denominator of the combination rule, in which 1-0.0877= 0.9123. The actual value associated with the focal element $\{A_1\}$ is subsequently given by 0.1767/ 0.9123 =0.1937. Similarly, the combination of the other bpa values of $m_1()$ and $m_2()$ can also be obtained, as shown in Table 16.

The reason to combine the bpa values of different criteria is to perform data fusion. Similarly, the combined bpa values of $m_{123}()$ can also be obtained by combining the bpa values of $m_{12}()$ with the bpa values of $m_3()$. In a similar way, the final bpa values can also be obtained, as shown in Table 17. The procedures were specified in the *Appendix*.

Step 5: The belief and plausibility measures

The final bpa values from combining the sub-bpa values of the nine criteria were calculated: $m_{12345678910}(\{A_1\})$=0.3261, $m_{12345678910}(\{A_2\})$=0.3183, $m_{12345678910}$

({A3})=0.0632, $m_{12345678910}$({ A1, A2}})=0.1119, $m_{12345678910}$({ A2, A3}})=0.0709, $m_{12345678910}$({ A1, A3}})= 0.0417, and $m_{12345678910}$({Θ}})= 0.0680. Accordingly, the belief and plausibility measures can be obtained by Eq.3 and Eq.4, along with the belief intervals of the three technologies: [Ble(A1), Pls(A1)]=[0.3216, 0.5477], [Ble(A2), Pls(A2)]=[0.3183, 0.5691], and [Ble(A3), Pls(A3)]=[0.0632, 0.2438].

Step 6: The degree of preference

The degrees of preference between each pair of the alternatives can be obtained by Eq. 41, as shown in the matrix P :

$$P = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \end{array} \begin{array}{ccc} A_1 & A_2 & A_3 \\ 0.5000 & 0.4810 & 1.0000 \\ 0.5190 & 0.5000 & 1.0000 \\ 0 & 0 & 0.5000 \end{array}$$

P_{ij} is the degree of preference A_i over A_j .

Step 7: Alternatives ranking

It is apparent that $P(1,3) > 0.5$, $P(2,1) > 0.5$ and $P(2,3) > 0.5$; it can be deduced that $A_1 \succ A_3$, $A_2 \succ A_1$ and $A_2 \succ A_3$ according to the principals for ranking the alternatives. Therefore, the final priority sequence of the three alternative energy sources for shipping from the most sustainable to the least is $A_2 \succ A_1 \succ A_3$, indicating that nuclear power has been recognized as the most sustainable scenario in this decision-making process, followed by LNG and wind power, and the priorities of nuclear power and LNG are much better than that of wind power. The results are determined by combining all the sub-bpa values of the nine criteria under incomplete information conditions; this method can successfully determine the most alternative energy source for shipping under incompletion that cannot be solved by the traditional MCDM methods.

Step 8: Sensitivity analysis and validating the results

In order to analyze the effects of the weights of the criteria on the bpa values of the focal elements, the bpa values of the focal elements under C_1 have been investigated by changing the weight of this criterion, and the results have been presented in Figure 7. It is apparent that the bpa values of the focal elements that represent the relative performances of the focal elements are very sensitive to the weight of C_1. Similarly, the bpa values of the focal elements under other criteria are also sensitive to the weights of the criteria. Thus, it could be concluded that the weights of the criteria have significant impacts on the relative performances of the focal elements. Therefore, the final priority sequence of the alternative energy sources for shipping may change if the weights of the criteria have been changed. Meanwhile, the weights of the criteria are highly dependent on the preferences and willingness of the decision-makers. Accordingly, the final priority sequence of the alternative energy sources for shipping may change when changing the decision-makers. In one word, the proposed method can help the decision-makers to select the most sustainable energy source for shipping according to their preferences and willingness. This is also the reason why the results determined by the proposed method are different from some other studies [43].

The weighted sum method has been used to rank the sustainability sequence of the three alternative energy sources based on the preference values presented in Table 13 and the weights of the criteria determined by TFAHP and AHP (see Figure 5); the results were presented in Figure 8. It is apparent that the final priority sequences of the three alternative energy sources for shipping based on the weights determined by TFAHP and AHP are the same as that determined by the proposed method in this study. To some extent, it could validate the feasibility of the proposed method and that the proposed method can incorporate incomplete information.

Three alternative energy sources were ranked by the proposed MCDM method; however it is worth pointing out that this is a generic method for sustainability assessment and ranking of alternative energy sources for shipping according to the preferences and opinions of the decision-makers/stakeholders, thus, this method can be popularized, and more alternative energy sources for shipping can be assessed by the developed method.

6. Conclusions

The Dempster-Shafer theory was combined with trapezoidal fuzzy analytic hierarchy analysis for selecting the most sustainable alternative energy sources for shipping under incomplete information. The proposed MCDM method can successfully achieve sustainability ranking of alternative energy sources for shipping, and the users are allowed to use linguistic terms to depict their preferences and opinions on the relative importance of the criteria for sustainability assessment. Meanwhile, the evaluation criterion system, consisting of 15 criteria in four aspects for sustainability assessment of alternative energy sources for shipping, was developed for sustainability assessment of alternative energy sources for shipping. To illustrate the developed methodology, three alternative energy sources, including LNG, nuclear power, and wind power were studied. Ten criteria, namely, maturity, reliability, and energy storage efficiency (technological aspect); infrastructure, capital cost, and bunker price (economic aspect); NO_x reduction and GHG emissions reduction (environmental aspect); and social acceptability and safety (social-political aspect) were employed for sustainability assessment of the alternative energy sources. The resulting priority sequence in descending order determined by the developed is nuclear power, LNG, and wind power.

Nuclear power was recognized as the most sustainable energy source for shipping, thus, the development of nuclear power based ships should be given high priority in future, and the following policy implications were proposed for popularizing the use of nuclear power:

(1) Setting special low/zero interest loan for the retrofitting of nuclear power based ships;

(2) Education and training on the stakeholders of ships (i.e. ship owners and sailors) for more knowledge about nuclear based ships, especially for mitigating the nuclear fear;

(3) Governmental subsidies for nuclear power based ships to increase the competitiveness of nuclear power as an alternative energy source for ships.

7. Discussion

The results are reasonable, as nuclear power normally performs better than other alternative energy sources in most aspects according to the literature review; it has significant strengths and advantages, except for capital cost and safety [43]. LNG, as a proven and feasible alternative solution for shipping, also shows excellent performances in many aspects of sustainability, though it has insufficient infrastructure and low energy storage efficiency [67, 71]. Wind power is highly dependent on weather conditions and is more suitable for supplementary power for ship propulsion. However, the results are not consistent to the work of Gu and Zhang [43]. In their study, renewable energy sources (e.g., wind power and solar power) are recognized as the most popular and attractive pathways, followed by LNG and nuclear according to their survey of questionnaire. It is worth noting that the attractiveness and acceptability cannot completely reflect the sustainability of each alternative energy source for shipping, and the emotional fear of the public to nuclear power is the main reason leading to its low attractiveness and acceptability. The difference is reasonable for several reasons: First, the studies use different criteria systems. This study employed 10 criteria of four aspects for sustainability assessment, whereas Gu and Zhang mainly focused on six macro-aspects. Second, the studies had different influences of weighting: This study considered the relative weights of the criteria for sustainability assessment by using TFAHP, whereas Gu and Zhang [43] used the traditional AHP method. Third, the studies used different ranking methods: This study used a hybrid multi-criteria decision making method by combining Dempster-Shafer theory and TFAHP for prioritizing the alternatives, whereas Gu and Zhang ranked these alternatives based on summing the priorities of each alternative energy sources with respect to the criteria. Lastly, each study had subjective characteristics in the decision-making process as the preferences and willingness of different decision-makers are different.

Therefore, this methodology can be popularized to select the most sustainable alternative energy source for shipping under conditions of uncertainty and incomplete information.

The future work of authors is to improve this method for two purposes: (i) the incorporation of the interdependences and interactions among the criteria for sustainability ranking of alternative energy sources, because there are various independences, interdependences and interactions among the criteria; and the use of the data of the alternatives with respect to each criterion, because the data used in the proposed multi-criteria decision making framework for prioritizing alternative energy sources for shipping are obtained based on subjective human judgments (both the relative priority of the focal elements under each criterion and the weights of the criteria), it can reflect the preferences of the decision-makers; however, some data of the alternatives with respect to parts of the criteria for sustainability assessment cannot be fully used.

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Appendix

Table A1: Intermediate results of the combination of the bpa values of $m_{12}()$ and $m_3()$

$m_{12}()/m_3()$	$\{A_1,A_3\}$: 0.0823	$\{A_2\}$: 0.1646	Θ :0.7530
$\{A_1\}$: 0.1937	$\{A_1\}$: 0.0159	$\varnothing$: 0.0319	$\{A_1\}$: 0.1459
$\{A_1,A_2\}$: 0.4832	$\{A_1\}$: 0.0398	$\{A_2\}$: 0.0795	$\{A_1,A_2\}$: 0.3638
Θ :0.3234	$\{A_1,A_3\}$: 0.0266	$\{A_2\}$: 0.0532	Θ : 0.2435

	$\{A_1\}$	$\{A_2\}$	$\{A_3\}$	$\{A_1, A_2\}$	$\{A_1, A_3\}$	$\{A_2, A_3\}$	Θ
m_{123} ( )	0.2082	0.1371	/	0.3758	0.0275	/	0.2515

Table A2: Intermediate results of the combination of the bpa values of $m_{123}()$ and $m_4()$

$m_{123}()/m_4()$	$\{A_2,A_3\}$:0.1227	$\{A_1\}$:0.0491	Θ:0.8282
$\{A_1\}$: 0.2082	$\varnothing$: 0.0255	$\{A_1\}$: 0.0102	$\{A_1\}$: 0.1724
$\{A_2\}$: 0.1371	$\{A_2\}$: 0.0168	$\varnothing$: 0.0067	$\{A_2\}$:0.1135
$\{A_1, A_2\}$:0.3758	$\{A_2\}$:0.0461	$\{A_1\}$:0.0185	$\{A_1, A_2\}$:0.3112
$\{A_1, A_3\}$:0.0275	$\{A_3\}$:0.0034	$\{A_1\}$:0.0014	$\{A_1, A_3\}$:0.0228
Θ:0.2515	$\{A_2,A_3\}$:0.0309	$\{A_1\}$:0.0123	Θ:0.2083

	$\{A_1\}$	$\{A_2\}$	$\{A_3\}$	$\{A_1, A_2\}$	$\{A_1, A_3\}$	$\{A_2, A_3\}$	Θ
$m_{1234}()$	0.2219	0.1823	0.0035	0.3216	0.0236	0.0319	0.2152

Table A3: Intermediate results of the combination of the bpa values of $m_{1234}()$ and $m_5()$

$m_5()/m_{1234}()$	$\{A_1\}$: 0.2219	$\{A_2\}$ 0.1823	$\{A_3\}$ 0.0035	$\{A_1, A_2\}$ 0.3216	$\{A_1, A_3\}$ 0.0236	$\{A_2, A_3\}$ 0.0319	Θ 0.2152
$\{A_1,A_3\}$:0.1343	$\{A_1\}$	$\varnothing$	$\{A_3\}$	$\{A_1\}$	$\{A_1, A_3\}$	$\{A_3\}$	$\{A_1,A_3\}$
$\{A_2\}$:0.0896	$\varnothing$	$\{A_2\}$	$\varnothing$	$\{A_2\}$	$\varnothing$	$\{A_2\}$	$\{A_2\}$
Θ : 0.7761	$\{A_1\}$	$\{A_2\}$	$\{A_3\}$	$\{A_1, A_2\}$	$\{A_1, A_3\}$	$\{A_2, A_3\}$	Θ

0.0298	0.0245	0.0005	0.0432	0.0032	0.0043	0.0289
0.0199	0.0163	0.0003	0.0288	0.0021	0.0029	0.0193
0.1722	0.1415	0.0027	0.2496	0.0183	0.0248	0.1670

	$\{A_1\}$	$\{A_2\}$	$\{A_3\}$	$\{A_1, A_2\}$	$\{A_1, A_3\}$	$\{A_2, A_3\}$	Θ
$m_{12345}()$	0.2572	0.2191	0.0079	0.2619	0.0529	0.0260	0.1752

Table A4: Intermediate results of the combination of the bpa values of $m_{12345}()$ and $m_6()$

$M_6()/m_{12345}()$	$\{A_1\}$:	$\{A_2\}$	$\{A_3\}$	$\{A_1, A_2\}$	$\{A_1, A_3\}$	$\{A_2, A_3\}$	Θ
$\{A_1,A_2\}$:0.0516	$\{A_1\}$	$\{A_2\}$	$\varnothing$	$\{A_1, A_2\}$	$\{A_1\}$	$\{A_1\}$	$\{A_1,A_2\}$
$\{A_3\}$:0.0774	$\varnothing$	$\varnothing$	$\{A_3\}$	$\varnothing$	$\{A_3\}$	$\{A_3\}$	$\{A_3\}$
Θ :0.8710	$\{A_1\}$	$\{A_2\}$	$\{A_3\}$	$\{A_1, A_2\}$	$\{A_1, A_3\}$	$\{A_2, A_3\}$	Θ

0.0133	0.0113	0.0004	0.0135	0.0027	0.0013	0.0090
0.0199	0.0170	0.0006	0.0203	0.0041	0.0020	0.0136
0.2240	0.1908	0.0069	0.2281	0.0461	0.0226	0.1526

	$\{A_1\}$	$\{A_2\}$	$\{A_3\}$	$\{A_1, A_2\}$	$\{A_1, A_3\}$	$\{A_2, A_3\}$	Θ
$m_{123456}()$	0.2560	0.2145	0.0289	0.2659	0.0489	0.0240	0.1619

Table A5: Intermediate results of the combination of the bpa values of m_{123456}() and m_7()

$M_7()/m_{123456}$ ( )	{A_1}:	{A_2}	{A_3}	{ A_1, A_2}	{ A_1, A_3}	{ A_2, A_3}	Θ
{ A_2,A_3}	$\varnothing$	{A_2}	{A_3}	{A_2}	{A_3}	{ A_2, A_3}	{ A_2, A_3}
{A_1}	{A_1}	$\varnothing$	$\varnothing$	{A_1}	{A_1}	$\varnothing$	{A_1}
Θ	{A_1}	{A_2}	{A_3}	{ A_1, A_2}	{ A_1, A_3}	{ A_2, A_3}	Θ

0.0604	0.0506	0.0068	0.0628	0.0115	0.0057	0.0382
0.0403	0.0338	0.0045	0.0419	0.0077	0.0038	0.0255
0.1553	0.1301	0.0175	0.1613	0.0297	0.0146	0.0982

	{A_1}	{A_2}	{A_3}	{ A_1, A_2}	{ A_1, A_3}	{ A_2, A_3}	Θ
$m_{1234567}$ ( )	0.3016	0.2713	0.0399	0.1797	0.0331	0.0652	0.1094

Table A6: Intermediate results of the combination of the bpa values of $m_{1234567}()$ and $m_8()$

$m_8()/m_{1234567}()$	$\{A_1\}$:	$\{A_2\}$	$\{A_3\}$	$\{A_1, A_2\}$	$\{A_1, A_3\}$	$\{A_2, A_3\}$	Θ
$\{A_2, A_3\}$	$\varnothing$	$\{A_2\}$	$\{A_3\}$	$\{A_2\}$	$\{A_3\}$	$\{A_2, A_3\}$	$\{A_2, A_3\}$
$\{A_1\}$	$\{A_1\}$	$\varnothing$	$\varnothing$	$\{A_1\}$	$\{A_1\}$	$\varnothing$	$\{A_1\}$
Θ	$\{A_1\}$	$\{A_2\}$	$\{A_3\}$	$\{A_1, A_2\}$	$\{A_1, A_3\}$	$\{A_2, A_3\}$	Θ

0.0593	0.0533	0.0078	0.0353	0.0065	0.0128	0.0215
0.0296	0.0267	0.0039	0.0177	0.0033	0.0064	0.0108
0.2127	0.1913	0.0281	0.1267	0.0233	0.0460	0.0771

	$\{A_1\}$	$\{A_2\}$	$\{A_3\}$	$\{A_1, A_2\}$	$\{A_1, A_3\}$	$\{A_2, A_3\}$	Θ
$m_{12345678}()$	0.3033	0.3097	0.0469	0.1402	0.0258	0.0889	0.0853

Table A7: Intermediate results of the combination of the bpa values of $m_{12345678}()$ and $m_9()$

$m_9()/m_{12345678}()$	$\{A_1\}$	$\{A_2\}$	$\{A_3\}$	$\{A_1, A_2\}$	$\{A_1, A_3\}$	$\{A_2, A_3\}$	Θ
$\{A_1, A_3\}$	$\{A_1\}$	$\varnothing$	$\{A_3\}$	$\{A_1\}$	$\{A_1, A_3\}$	$\{A_3\}$	$\{A_1, A_3\}$
$\{A_2\}$	$\varnothing$	$\{A_2\}$	$\varnothing$	$\{A_2\}$	$\varnothing$	$\{A_2\}$	$\{A_2\}$
Θ	$\{A_1\}$	$\{A_2\}$	$\{A_3\}$	$\{A_1, A_2\}$	$\{A_1, A_3\}$	$\{A_2, A_3\}$	Θ
	0.0195 0.0098 0.2740	0.0199 0.0100 0.2798	0.0030 0.0015 0.0424	0.0090 0.0045 0.1267	0.0017 0.0008 0.0233	0.0057 0.0029 0.0803	0.0055 0.0027 0.0771
	$\{A_1\}$	$\{A_2\}$	$\{A_3\}$	$\{A_1, A_2\}$	$\{A_1, A_3\}$	$\{A_2, A_3\}$	Θ
$m_{123456789}()$	0.3125	0.3098	0.0528	0.1309	0.0315	0.0830	0.0796

Table A8: Intermediate results of the combination of the bpa values of $m_{123456789}()$ and $m_{10}()$

$M_{10}()/m_{123456789}()$	{A_1}	{A_2}	{A_3}	{ A_1, A_2}	{ A_1, A_3}	{ A_2, A_3}	Θ
{ A_1,A_3}	{A_1}	∅	{A_3}	{A_1}	{ A_1, A_3}	{A_3}	{ A_1,A_3}
{A_2}	∅	{A_2}	∅	{A_2}	∅	{A_2}	{A_2}
Θ	{A_1}	{A_2}	{A_3}	{ A_1, A_2}	{ A_1, A_3}	{ A_2, A_3}	Θ

0.0386	0.0383	0.0065	0.0162	0.0039	0.0103	0.0098
0.0257	0.0255	0.0043	0.0108	0.0026	0.0068	0.0066
0.2482	0.2460	0.0419	0.1040	0.0250	0.0659	0.0632

	{A_1}	{A_2}	{A_3}	{ A_1, A_2}	{ A_1, A_3}	{ A_2, A_3}	Θ
$m_{12345678910}()$	0.3261	0.3183	0.0632	0.1119	0.0417	0.0709	0.0680

Figure Captions

Figure 1: The three spheres of sustainability in a triple bottom line assessment. **Source:** Ref. [30].

Figure 2: Four dimensions of sustainability.

Figure 3: Trapezoidal fuzzy numbers $\tilde{a} = (a_1, a_2, a_3, a_4)$

Figure 4: Comparison of the weights of the four aspects determined by TFAHP and AHP.

Figure 5: Comparison of the weights of the 10 criteria determined by TFAHP and AHP.

Figure 6: DS model of selecting the most sustainable technology for SO_x reduction.

Figure 7: The bpa values of the focal elements under C_1 with the change of the weight of this criterion.

Figure 8: The weighted score of the three alternatives based on the weights determined by TFAHP and AHP.

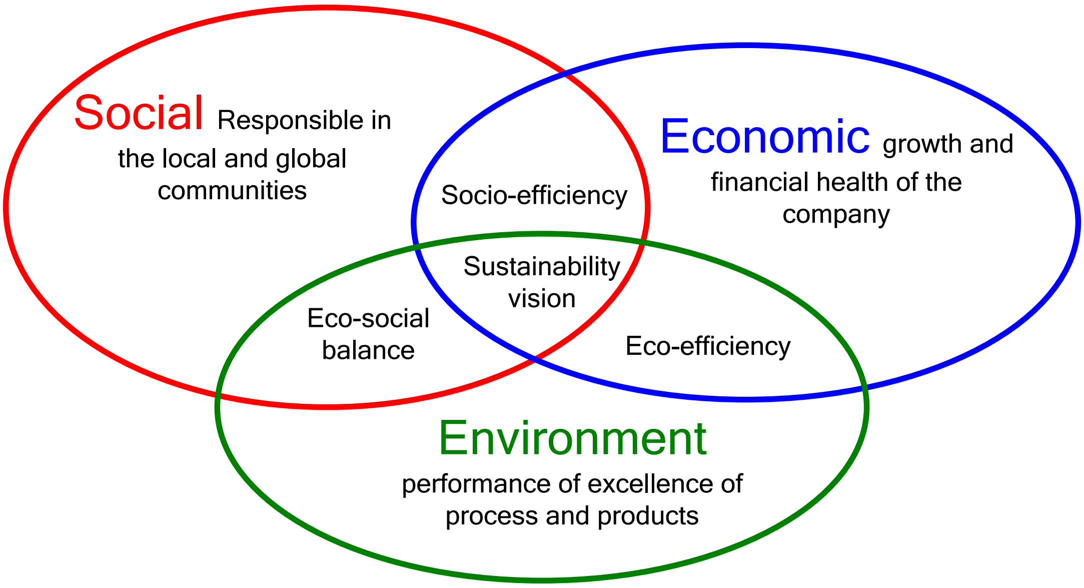

Figure 1: The three spheres of sustainability in a triple bottom line assessment. **Source:** Ref. [30].

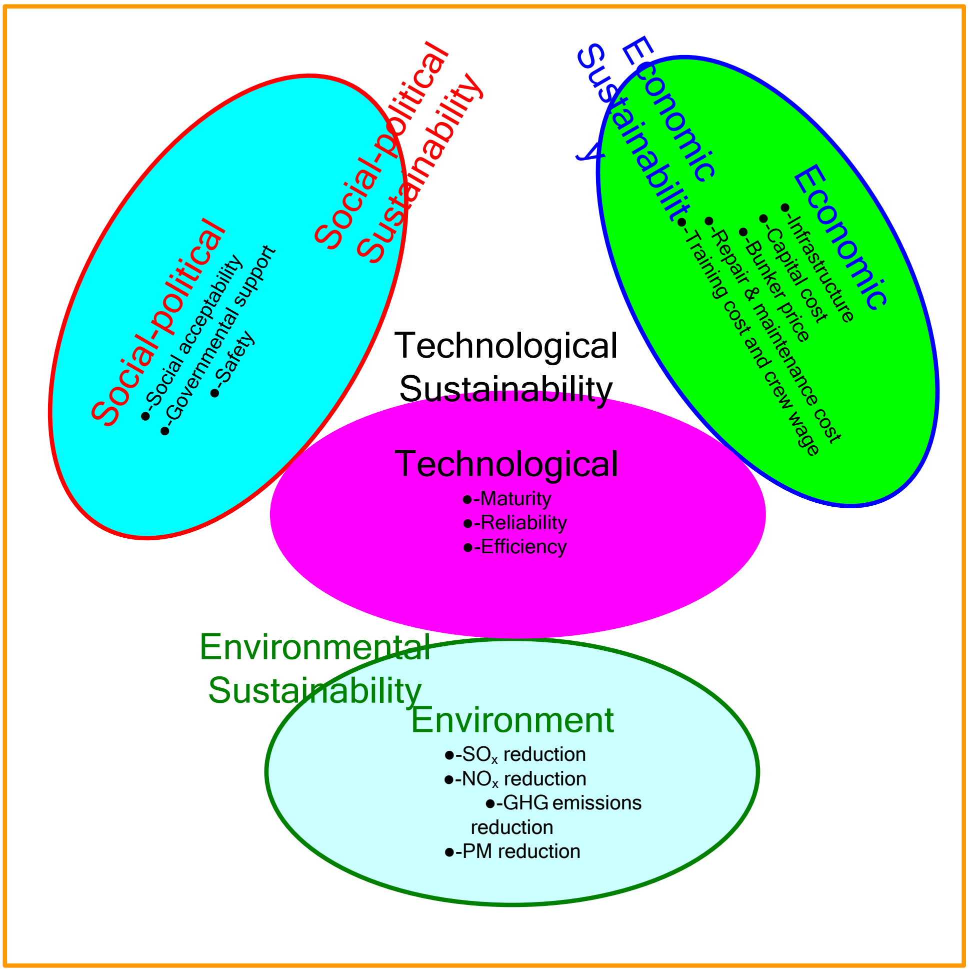

Figure 2: Four dimensions of sustainability.

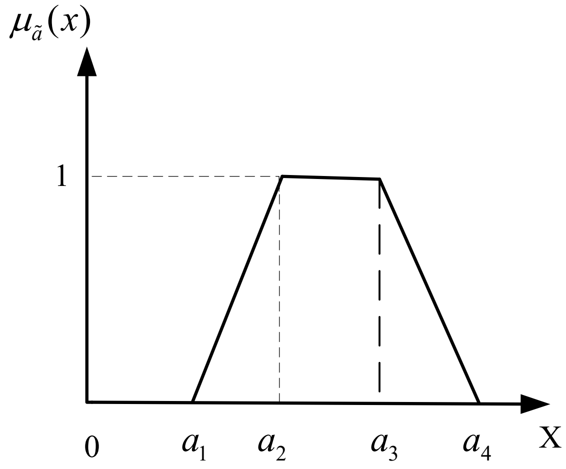

Figure 3: Trapezoidal fuzzy numbers $\tilde{a} = (a_1, a_2, a_3, a_4)$

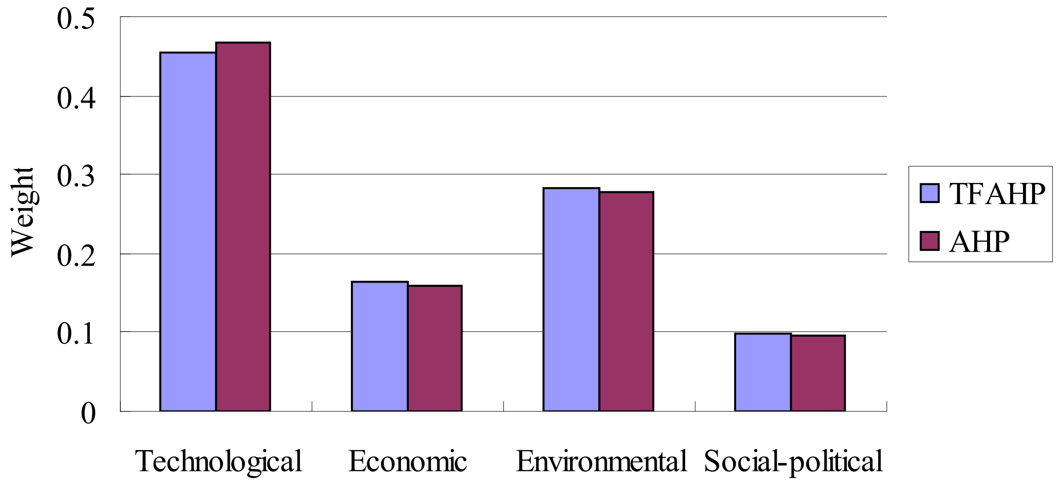

Figure 4: Comparison of the weights of the four aspects determined by TFAHP and AHP.

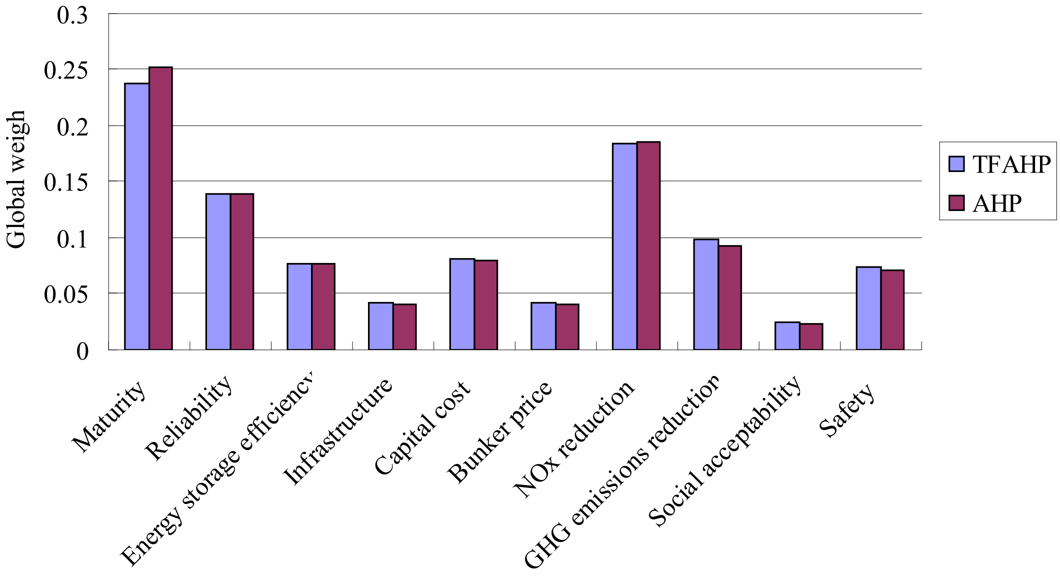

Figure 5: Comparison of the weights of the 10 criteria determined by TFAHP and AHP.

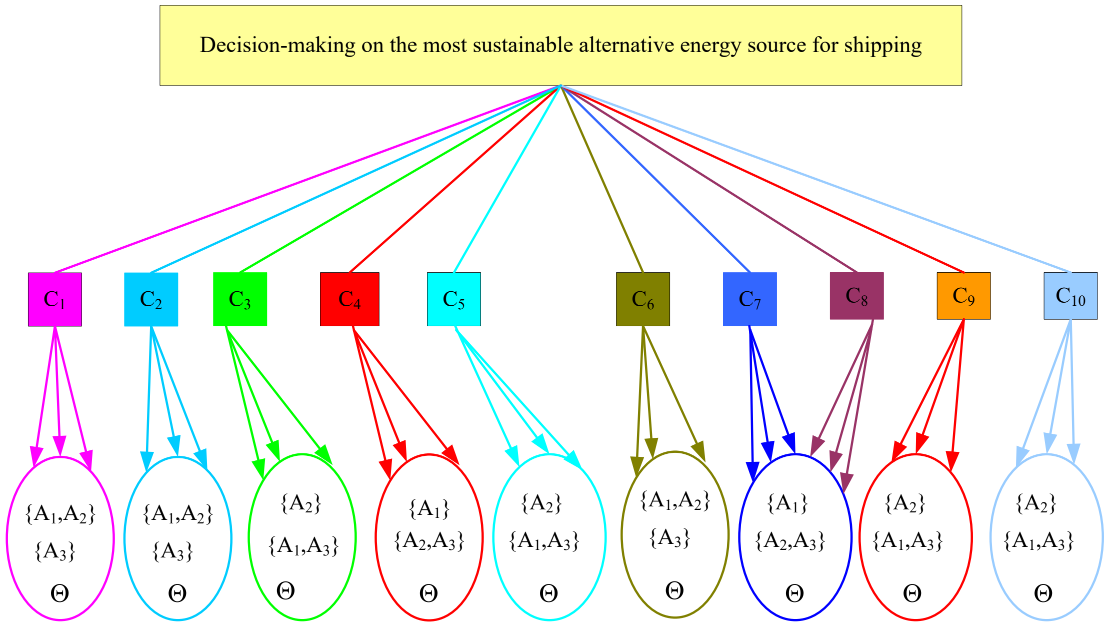

Figure 6: DS model of selecting the most sustainable technology for SO_x reduction.

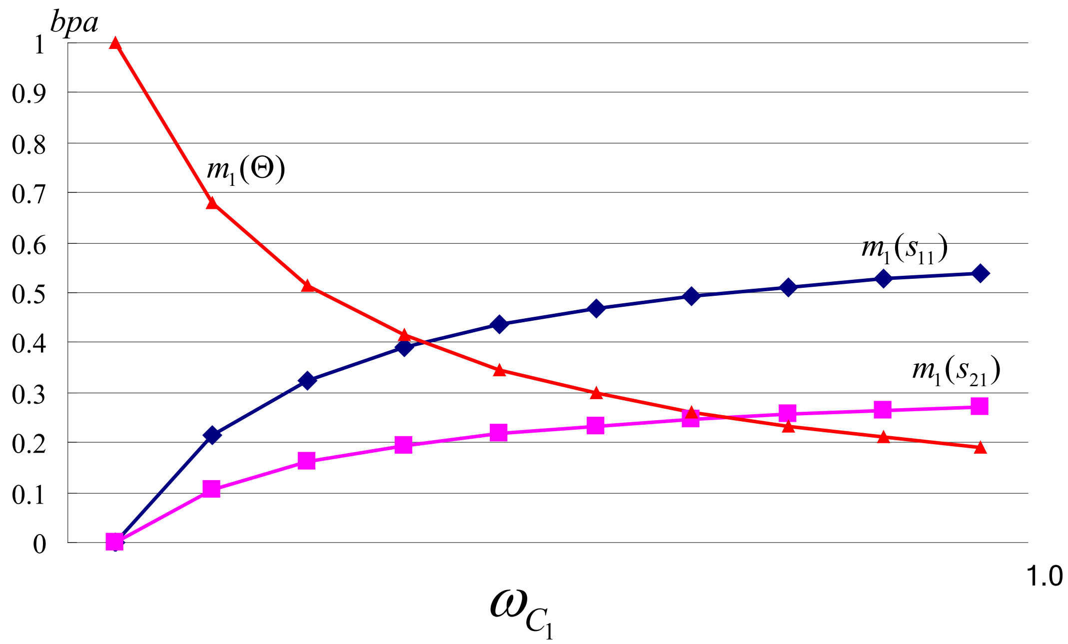

Figure 7: The bpa values of the focal elements under C_1 with the change of the weight of this criterion.

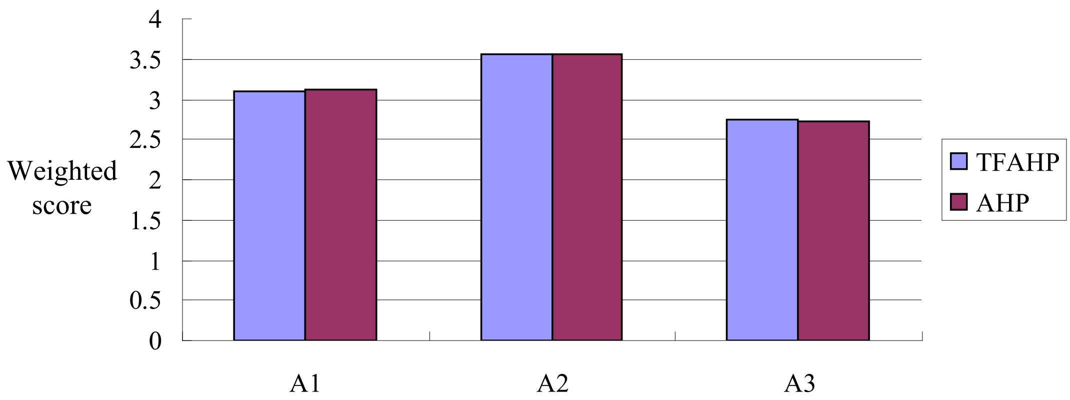

Figure 8: The weighted score of the three alternatives based on the weights determined by TFAHP and AHP.