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A Fuzzy Multi-Criteria Method for Sustainable Ferry Operator Selection: A Case Study

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Abstract: This study is motivated by the Zhuhai municipal government, which needs to select a sustainable ferry operator. Previous research has ignored the evaluation and selection of ferry operators. In addition, since ferry operator evaluation involves conflicting qualitative and quantitative criteria, and there may be uncertainty and ambiguity in the evaluation of criteria by experts, a fuzzy multi-criteria decision-making (MCDM) approach is required to address this challenge. To this end, this paper proposes an integrated MCDM framework model to evaluate and select the best ferry operator. First, a ferry operator evaluation index system with 15 sub-criteria is constructed according to literature and expert opinions; then the fuzzy analytic hierarchy process (FAHP) is used to determine the subjective weight of the criteria, and the entropy weight (EW) method is used to calculate the objective weight of the criteria. We use the linear weighting method to obtain the comprehensive weights of the criteria; finally, the fuzzy technique for order preference by similarity to ideal solution (FTOPSIS) method is adapted to determine the best ranking of the alternatives. This paper takes the Wanshan Islands in Zhuhai as a real case study to verify the proposed FAHP-EW-FTOPSIS method. The results show that the proposed method can be effectively applied to the evaluation and selection of ferry operators. Sensitivity analysis of criteria weights demonstrates the effectiveness and robustness of the proposed framework model. Key findings based on the research provide management insights that can benefit relevant stakeholders. This is the first paper to study the evaluation and selection of ferry operators. Hence, the evaluation index system and integrated framework model proposed in this paper can make important contributions to the evaluation of ferry operators.

Keywords: ferry operator selection; sustainability; multi-criteria decision-making; criteria weights; fuzzy TOPSIS

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1. Introduction

Maritime transport is essential for mobility between island and island, and between island and inland [1]. Among the maritime transport services, ferry transport is considered a convenient and flexible way of transporting people and goods between terminals/ports and connecting remote islanders and inland areas [2]. It is worth noting, however, that since the COVID-19 pandemic, many ferry transports have been forced to cease service due to declining passenger numbers and reduced government subsidies for ferry travel. Nonetheless, ferry transport still plays an irreplaceable role in securing between islands, and islands and inland. In recent years, ferry transport has received more and more attention from scholars in the public transport sector [3–7]. While these studies focusing on ferry transport do make an important contribution to ferry services, the selection of ferry operators has been overlooked. This paper is motivated by the Zhuhai municipal government, which needs to select a sustainable ferry operator. Developing sustainable ferry transport services is a common challenge for ferry operators and local authorities. The Zhuhai Municipal Government plans to select a suitable ferry operator through appropriate methods after the original ferry operator contract expires to achieve: (1) overall improvement in the quality of ferry transportation services; (2) the reduction of carbon emissions during ferry transportation. However, the Zhuhai municipal government currently has limited method to select ferry operators. Hence, a suitable integrated framework model is urgently needed to select sustainable ferry operators.

Ferry operator selection is regarded as a multi-criteria decision making (MCDM) problem due to the need to evaluate both qualitative and quantitative criteria. The theories and methods of MCDM are widely used in many fields such as energy [8–10], site selection [11–13], risk evaluation [14–17], and sustainable supplier selection [18–21], etc. In the MCDM problem, it is difficult for experts to give accurate crisp evaluations due to the subjectivity and ambiguity of the qualitative criteria. For example, when evaluating the appearance of a product, experts can only give verbal descriptions, but cannot give specific numerical evaluations. In practice, linguistic terms are often used to describe qualitative criteria. Although linguistic terms can contribute to describing qualitative criteria, ambiguity remains in its linguistic terms. In order to solve the ambiguity in the evaluation of linguistic terms for decision makers, fuzzy set theory, proposed by Zadeh [22], has been widely used in practice. Therefore, this paper converts linguistic terms into triangular fuzzy numbers (TFNs) to solve ambiguous qualitative criteria. Moreover, in the MCDM problem, two problems need to be solved: one is to determine the criteria weight; the other is to rank the alternatives. Regarding the determination method of criteria weights, previous studies have developed many different weight determination methods. For example, Ho et al. [23], Feng [24], Paul et al. [25], and Fard et al. [26] applied fuzzy analytic hierarchy process (FAHP) to calculate criteria weights; Lee and Chang [27], Dang et al. [28], and Omidi et al. [29] used entropy weight (EW) method to obtain objective criteria weights. Best worst method (BWM) [20], integrated determination of objective criteria weights [30], and decision-making trial and evaluation laboratory (DEMATEL) [31] are also used to determine criteria weights. Regarding the alternative ranking method, the previous literature has reported many methods, such as fuzzy technique for order preference by similarity to ideal solution (TOPSIS) [32], Vlsekriterijumska optimizacijia I kompromisno resenje (VIKOR) [33], preference ranking organization method for enrichment of evaluations (PROMETHEE) [34], multi-objective optimization by ratio analysis plus full multiplicative form (MULTIMOORA) [35], complex proportional assessment (COPRAS) [36], fuzzy axiomatic design (FAD) [37], and ELimination Et Choix Traduisant la REalité–ELimination and Choice Expressing the Reality (ELECTRE) [38], etc. The previous literature on determining weights and alternative ranking methods made important contributions to this study.

Unfortunately, although ferry operator evaluation is an important scientific issue that benefits stakeholders, to date, there are no literature reports on this issue. Even though there are many studies on the selection of service providers in the literature, a ferry service provider can be an enterprise that provides ferry leasing, ferry operation management, and other related services, while a ferry operator is an enterprise that manages ferry services. Strictly speaking, ferry service providers cover a wider range than ferry operators. Therefore, this paper focuses on ferry operator selection rather than ferry service providers. Thus, this paper aims to develop a suitable MCDM method to fill the research gap of ferry operator evaluation. The aim of this article is to address the following questions: (1) How to select a suitable and sustainable ferry operator evaluation index system? (2) How to construct an effective MCDM integrated analysis framework to select suitable ferry operators? (3) How do criteria weights affect decision outcomes? (4) How do stakeholders benefit from the proposed approach?

The purpose of this study is to develop a FAHP-EW-FTOPSIS method to build an integrated framework model to select sustainable ferry operators. We first use FAHP to calculate the criteria subjective weight, then use the EW method to determine the criteria objective weight, these two methods can complement each other well, and finally use the linear weighting method to determine the comprehensive weight. TOPSIS is then used to rank the alternatives after obtaining the criterion weights. The main research contributions of this paper are highlighted as follows:

(1) To the best of our knowledge, previous literature focused on: (i) ferry transport pricing [7] (ii) ferry transport safety [1], (iii) ferry transport fleet [2], and (iv) ferry network design problem [39], etc., but ignored the evaluation of ferry operators despite this being a complex MCDM issue. Naturally, this is the first paper that investigates the evaluation of ferry operators from a sustainability perspective.

(2) In view of the superior performance of FTOPSIS in alternative solutions, it has been widely used in practice [40–45]. Again to the best of our knowledge, this is the first FAHP-EW-FTOPSIS-based MCDM technique proposed to select the best ferry operator in an attempt to extent the field of application of the FTOPSIS method. Moreover, we also build an effective integrated framework model for ferry operator evaluation for better implementation.

(3) Evaluation criteria are significantly important for ferry operator selection. Given that there is currently no literature report on the evaluation index system for ferry operators. Thus, this is the first paper that constructs an evaluation index system for ferry operators based on the perspective of sustainability.

2. Literature Review

This section aims to review the related literature from the method of determining criteria weights, alternative ranking method, and ferry operator evaluation.

2.1. Method of Determining Criteria Weights

Since criteria weights have an important influence on the final ranking of alternatives, it is very important to determine criteria weights by using a suitable method. Generally speaking, there are many methods to determine criteria weights. Regarding the subjective weighting method, there are many studies applying this method to determine the criteria weights, such as AHP [46], analytic network process (ANP) [47], Delphi method [48], and DEMATEL method [49], etc. Although as a subjective weighting method, AHP, ANP, Delphi method, and DEMATEL method show flaws in determining criteria weights, these methods still have advantages in determining criteria weights. The DEMATEL method proposed by Gabus and Fontela [50] can better deal with the logical relationship between the factors and the direct influence matrix. Thus, this method is a useful MCDM tool that has been applied in many fields, such as personnel selection [51], alternative fuel evaluation [52], and analysis of influencing factors of electric vehicle charging station [31], etc. To reflect the possible hierarchical structure between various criteria, Wan et al. [53] used ANP to determine the weight of each criterion and sub-criterion in supplier selection. Recently, many studies have reported the application of ANP to various MCDM problems, such as engineering characteristics of wheelchair design [54], wind farm site selection [55], and urban ecological security assessment [56]. Moreover, FAHP is a concise and practical method of systematic analysis. Noori et al. [41], Ke et al. [57], and Kabir et al. [58] adopted the FAHP to determine the importance of the criteria.

Objective weighting methods include principal component analysis method [59], multi-objective planning method and entropy weight (EW) method [60], etc. EW method, as an objective weighting method, has been applied to many research fields. For example, to avoid subjective factors and solve the aggregation problem of cross efficiency, Song et al. [61] applied the EW method to determine criteria weights. Huang et al. [62] applied the EW method to calculate the weight of each criterion and evaluated the operation performance of the urban rail transit system through TOPSIS method. Suneesh and Sivapragash [63] applied equal weight method, EW method, and AHP to determine the weight of parameters. Indeed, the EW method is relatively simple and easy to use [64]. Thus, EW method will be used to determine the objective criteria weights.

In view of the above literature review, although it is reasonable to use the FAHP method and the EW method to determine criteria weights, respectively, the FAHP method can reflect the ambiguity of the criteria, but it cannot objectively reflect the data information of the indicators, so the weights obtained may be different in reality. Moreover, EW method considers data information of the indicator, but ignores ambiguity of the criteria, and the weight obtained may differ from what decision makers expected. To obtain accurate criteria weights, therefore, this paper combines the FAHP method and the EW method to effectively solve the problem of allocating indicator weights.

2.2. Application of TOPSIS Method

Since TOPSIS was first proposed by Hwang and Yoon [65], this method has been widely applied in many fields, such as supplier selection [66], site selection [67], and risk evaluation [68]. Since the decision information is usually accompanied by fuzzy concepts, the traditional TOPSIS method may not be applicable. Thus, Chen [69] extended the TOPSIS method to the fuzzy environment. Ervural et al. [70] studied energy planning and energy alternatives, weighted each criterion through ANP, and then used TOPSIS to rank alternative energy sources. Gupta [71] used BWM to determine the criteria weights in green human resource management and adopted TOPSIS to assess organizational management. Kutlu Gündoğdu and Kahraman [72] extended the TOPSIS method to the spherical fuzzy set environment and compared it with the intuitionistic fuzzy TOPSIS method. Rani et al. [73] used an extended fuzzy TOPSIS method to select suitable renewable energy sources. Sagnak et al. [74] developed an analytical framework for e-waste recycling center locations, applied BWM to determine criterion weights, and used the FTOPSIS method to rank candidate locations. Bilgili et al. [75] used the TOPSIS method to select optimal renewable energy sources in the context of intuitionistic fuzzy sets.

Based on the above literature review, it can be seen that the TOPSIS method has been applied to many research fields in different fuzzy environments. However, criteria evaluation information often cannot be expressed in one linguistic term, but requires many different forms to express, such as crisp numerical values, intuitionistic fuzzy sets, TFNs, etc. Thus, this paper will extend the TOPSIS method under hybrid decision-making information environment.

2.3. Ferry Operator Evaluation

Since the selection of suitable ferry operators is crucial for ferry services, next, we will review the relevant literature from two aspects selected from ferry services and ferry operator evaluation to obtain valuable information. Regarding ferry services, Lazim and Wahab [76] developed a fuzzy MCDM method to evaluate the quality of ferry services, and the evaluation results can help ferry operators to improve their quality. Lo et al. [77] developed a ferry network service model with stochastic demand and applied the proposed method to the Hong Kong ferry network design. The results show that the proposed method has advantages in terms of computational efficiency. Huang et al. [78] investigate the key factors in improving the quality of high-speed ferry service and make management recommendations for relevant stakeholders. Chu et al. [79] studied the design of ferry networks with candidate service arcs and validated it with the Zhuhai Islands as a case, and the results verified the effectiveness of the proposed method. Škurić et al. [2] constructed a mixed integer programming model to maximize ferry operator profits. Aslaksen et al. [80] investigated transport services with fixed schedules and on-demand ferries and assessed the size of ferries in different scenarios. There is no doubt that these studies have made important contributions to ferry services. Regarding ferry operator evaluation, to the best of our knowledge, there are no literature reports on the evaluation of ferry operators. Thus, this paper is the first to study the evaluation of ferry operators.

3. Methodology

This section aims to introduce the criteria weight determination method, fuzzy TOPSIS, and integrated framework of ferry operator evaluation.

3.1. Criteria Weight Determination Method

In this paper, FAHP is used to calculate the subjective weight of the criteria, the EW method is used to determine the objective weight of the criteria; finally, the comprehensive weight of the criteria is determined in a weighted manner. Next, the FAHP and EW methods will be introduced. Assume that there are m alternatives $A = (A_1, A_2, \cdots, A_m)$, n criteria $C = (c_1, c_2, \cdots, c_n)$ with a weight vector $W = (w_1, w_2, \cdots, w_n)$, and K experts $E = (e_1, e_2, \cdots, e_k)$ with a weight vector $W = \left(w^1, w^2, \cdots, w^k\right)$.

3.1.1. Fuzzy Analytic Hierarchy Process

Due to differences in the knowledge background and practical experience of experts, there may be ambiguity in the assessment of the criteria. In order to reduce the decision-making risk brought about by this difference, it is necessary to invite experts from different fields for evaluation.

(1) Build the hierarchy analysis structure of criteria and sub-criteria respectively. The expert's linguistic terms were transformed with the TFNs in Table 1 [81]. This paper uses the triangular fuzzy scale in the literature [81], because: (1) the scale has been widely used; (2) in the implementation process, the evaluation experts also unanimously selected this triangular fuzzy scale; (3) the triangular fuzzy scale can reflect the difference between the criteria degree of importance. Aggregate evaluation term of experts thus is given by Equation (1).

Table 1. The expert's linguistic terms.

Linguistic Scales	Triangular Fuzzy Scale	Triangular Fuzzy Reciprocal Scale
Equal importance	(1, 1, 1)	(1, 1, 1)
Weak importance	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly more importance	(1, 3/2, 2)	(1/2, 2/3, 1)
More importance	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Strongly more importance	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely more importance	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

$$a_{ij} = \sum_{k=1}^{K} w^k a_{ijk}, b_{ij} = \sum_{k=1}^{K} w^k b_{ijk}, c_{ij} = \sum_{k=1}^{K} w^k c_{ijk}, \tag{1}$$

where w^k represents the weight of expert k, and $\sum_{k=1}^{K} w^k = 1, k = 1, 2, \cdots, K$. $\left(a_{ijk}, b_{ijk}, c_{ijk}\right)$ represents the TFN evaluated by expert k. Let $Y_{ij} = \left(a_{ij}, b_{ij}, c_{ij}\right)$ represent the integrated fuzzy number.

(2) The fuzzy synthetic extent value of the i-th P_i object is given by

$$P_i = \sum_{j=1}^{m} Y_{ij} \times \left[\sum_{i=1}^{n}\sum_{j=1}^{m} Y_{ij}\right]^{-1}, \tag{2}$$

$$\sum_{j=1}^{m} Y_{ij} = \left(\sum_{j=1}^{m} a_{ij}, \sum_{j=1}^{m} b_{ij}, \sum_{j=1}^{m} c_{ij}\right), \tag{3}$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} Y_{ij}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} c_{ij}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} b_{ij}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} a_{ij}}\right). \tag{4}$$

(3) The degree of possibility of $(a_1, b_1, c_1) = P_1 \leq P_2 = (a_2, b_2, c_2)$ is given by

$$V(P_2 \geq P_1) = \begin{cases} 0, & \text{if } a_1 \geq c_2 \\ 1, & \text{if } b_2 \geq b_1 \\ \frac{a_1 - c_2}{(b_2 - c_2) - (b_1 - a_1)}, & \text{otherwise} \end{cases}. \quad (5)$$

(4) Let $d'(z_i) = \min V(P_i \geq P_l),\ l = 1, 2, \cdots, n,\ i \neq k$, then the weight vector is given by

$$w' = \left[d'(z_1), d'(z_2), \cdots, d'(z_n)\right]^T. \quad (6)$$

$$\min V(P \geq P_i) = V[(P \geq P_1) \text{ and } (P \geq P_2) \text{ and} \cdots \text{and } (P \geq P_k)]. \quad (7)$$

(5) Let w_j^s denote subjective criteria weight, and the normalized subjective criteria weight vector is given by

$$w_j^s = \left(w_1^s, w_2^s, \cdots, w_j^s\right) = \left(\frac{d'(z_1)}{\sum_{i=1}^n d'(z_n)}, \frac{d'(z_2)}{\sum_{i=1}^n d'(z_n)}, \cdots, \frac{d'(z_n)}{\sum_{i=1}^n d'(z_n)}\right) \quad (8)$$

3.1.2. Entropy Weight Method

In this paper, the EW method is used to calculate the criteria objective weight. Criteria's performance is judged by using the linguistic terms in Table 2. The reason why this paper chooses the triangular fuzzy scale in Table 2 is: (1) the evaluation experts reached a consensus after many discussions; (2) due to the ambiguity of the experts on the evaluation criteria, there must be overlap between two adjacent triangular fuzzy scales. The calculation process is as follows:

Table 2. Linguistic terms and corresponding TFNs used to assess criteria performance.

Linguistic Terms	Very High (VH)	High (H)	General (G)	Low (L)	Very low (VL)
TFNs	(0.8, 0.9, 1.0)	(0.6, 0.7, 0.9)	(0.4, 0.5, 0.7)	(0.2, 0.3, 0.5)	(0, 0.1, 0.3)

(1) Experts give the evaluation matrix $\overline{U}$ according to the criteria performance of the alternatives, then de-fuzzify the obtained fuzzy matrix, and finally aggregate the evaluation information of all experts. Finally, a matrix U with crisp values is obtained.

$$\overline{U} = \begin{bmatrix} u_{11}^k & u_{12}^k & \cdots & u_{1n}^k \\ u_{21}^k & u_{22}^k & \cdots & u_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ u_{m1}^k & u_{m2}^k & \cdots & u_{mn}^k \end{bmatrix} \quad (9)$$

$$u_{ij}^k = \frac{a_{ij}^k + 4b_{ij}^k + c_{ij}^k}{6}, \quad (10)$$

$$u_{ij} = \sum_{k=1}^{K} w^k u_{ij}^k. \quad (11)$$

(2) Normalize the matrix U by the following equation:

$$u_{ij}^* = \begin{cases} \frac{u_{ij} - \min_j u_{ij}}{\max_j u_{ij} - \min_j u_{ij}} & Benefit\ criteria \\ \frac{\max_j u_{ij} - u_{ij}}{\max_j u_{ij} - \min_j u_{ij}} & Cost\ criteria \end{cases}, \quad (12)$$

(3) The entropy of each criterion E_j is given by

$$E_j = -\frac{1}{\ln m}\sum_{i=1}^{m}\frac{u_{ij}^*}{\sum_{i=1}^{m}u_{ij}^*}\ln\frac{u_{ij}^*}{\sum_{i=1}^{m}u_{ij}^*}. \quad (13)$$

(4) Let w_j^o denote objective criteria j's weight, which is determined by the following equation:

$$w_j^o = \frac{1-E_j}{n-\sum_{j=1}^{n}E_j}. \quad (14)$$

3.1.3. Comprehensive Criteria Weight

Let $\beta(0 \le \beta \le 1)$ denote the decision maker's preference for subjective weights, and $1-\beta$ denote the decision maker's preference for objective weights. We use the following equation to determine the final criteria weights.

$$w_j = \beta w_j^s + (1-\beta)w_j^o. \quad (15)$$

3.2. Fuzzy TOPSIS

The main calculation steps of the TOPSIS method are as follows:

(1) Build initial fuzzy evaluation matrix U' of the alternatives.

$$U' = \begin{bmatrix} u'_{11} & u'_{12} & \cdots & u'_{1n} \\ u'_{21} & u'_{22} & \cdots & u'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u'_{m1} & u'_{m2} & \cdots & u'_{mn} \end{bmatrix} = \begin{bmatrix} (a'_{11},b'_{11},c'_{11}) & (a'_{12},b'_{12},c'_{12}) & \cdots & (a'_{1n},b'_{1n},c'_{1n}) \\ (a'_{21},b'_{21},c'_{21}) & (a'_{22},b'_{22},c'_{22}) & \cdots & (a'_{2n},b'_{2n},c'_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (a'_{m1},b'_{m1},c'_{m1}) & (a'_{m2},b'_{m2},c'_{m2}) & \cdots & (a'_{mn},b'_{mn},c'_{mn}) \end{bmatrix}, \quad (16)$$

where $u'_{ij} = \left(a'_{ij}, b'_{ij}, c'_{ij}\right)$, $a'_{ij} = \sum_{k=1}^{K} w^k a_{ijk}$, $b'_{ij} = \sum_{k=1}^{K} w^k b_{ijk}$, and $c'_{ij} = \sum_{k=1}^{K} w^k c_{ijk}$.

(2) Normalize initial fuzzy evaluation matrix U'

$$u''_{ij} = \begin{cases} \left(\frac{a'_{ij}}{\max_i c'_{ij}}, \frac{b'_{ij}}{\max_i c'_{ij}}, \frac{c'_{ij}}{\max_i c'_{ij}}\right) & Benefit\ criteria \\ \left(\frac{\min_i a'_{ij}}{c'_{ij}}, \frac{\min_i a'_{ij}}{b'_{ij}}, \frac{\min_i a'_{ij}}{a'_{ij}}\right) & Cost\ criteria \end{cases}, \quad (17)$$

Then, the normalized fuzzy decision matrix U'' can be expressed as

$$U'' = \begin{bmatrix} u''_{11} & u''_{12} & \cdots & u''_{1n} \\ u''_{21} & u''_{22} & \cdots & u''_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u''_{m1} & u''_{m2} & \cdots & u''_{mn} \end{bmatrix} = \begin{bmatrix} (a''_{11},b''_{11},c''_{11}) & (a''_{12},b''_{12},c''_{12}) & \cdots & (a''_{1n},b''_{1n},c''_{1n}) \\ (a''_{21},b''_{21},c''_{21}) & (a''_{22},b''_{22},c''_{22}) & \cdots & (a''_{2n},b''_{2n},c''_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (a''_{m1},b''_{m1},c''_{m1}) & (a''_{m2},b''_{m2},c''_{m2}) & \cdots & (a''_{mn},b''_{mn},c''_{mn}) \end{bmatrix}. \quad (18)$$

(3) Determine the weighted normalize matrix $\overline{C}$

$$\overline{C} = \begin{bmatrix} (w_1a''_{11},w_1b''_{11},w_1c''_{11}) & (w_2a''_{12},w_2b''_{12},w_2c''_{12}) & \cdots & (w_na''_{1n},w_nb''_{1n},w_nc''_{1n}) \\ (w_1a''_{21},w_1b''_{21},w_1c''_{21}) & (w_2a''_{22},w_2b''_{22},w_2c''_{22}) & \cdots & (w_na''_{2n},w_nb''_{2n},w_nc''_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (w_1a''_{m1},w_1b''_{m1},w_1c''_{m1}) & (w_2a''_{m2},w_2b''_{m2},w_2c''_{m2}) & \cdots & (w_na''_{mn},w_nb''_{mn},w_nc''_{mn}) \end{bmatrix}, . \quad (19)$$

(4) Defuzzification by the following equation:

$$\mathrm{h_{ij}} = \frac{\mathrm{w_j a''_{ij}} + 4\mathrm{w_j b''_{ij}} + \mathrm{w_j c''_{ij}}}{6}. \quad (20)$$

(5) Determine the fuzzy positive ideal solution h_j^+ and negative ideal solution h_j^-, respectively.

$$\begin{cases} h_j^+ = \left\{ (\max_i h_{ij} | j \text{ is benefit criteria}), (\min_i h_{ij} | j \text{ iscost criteria}) \right\} \\ h_j^- = \left\{ (\min_i h_{ij} | j \text{ is benefit criteria}), (\max_i h_{ij} | j \text{ iscost criteria}) \right\} \end{cases}, \quad (21)$$

(6) The distance of alternative from positive and negative ideal solution d_i^+, d_i^- is computed by

$$\begin{cases} d_i^+ = \left\{ \sum_{j=1}^{m} \left(h_j^+ - h_{ij} \right)^2 \right\}^{\frac{1}{2}} \\ d_i^- = \left\{ \sum_{j=1}^{m} \left(h_j^- - h_{ij} \right)^2 \right\}^{\frac{1}{2}} \end{cases}. \quad (22)$$

(7) Compute the closeness coefficient of each alternative S_i by

$$S_i = \frac{d_i^-}{d_i^+ + d_i^-}, \quad (23)$$

where $0 \le S_i \le 1$, the larger the S_i, the better the ranking of the alternatives.

3.3. Integrated Framework of Ferry Operator Evaluation

Since the evaluation of ferry operators is a complex MCDM problem, it involves the construction of evaluation index system, the determination of criteria weights, and the ranking of alternatives. Therefore, there is an urgent need for an integrated framework model to clearly demonstrate the linkages between these elements to support decision makers in the process of implementing ferry operator evaluations. The integrated framework model of ferry operator evaluation constructed in this paper is shown in Figure 1.

Figure 1. Integrated framework model of ferry operator evaluation.

4. Discussion

The criterion is the basis of ferry operator evaluation, therefore it is extremely important to establish a scientific and systematic evaluation index system to reflect the qualitative and quantitative criteria of ferry operator evaluation. Although there are many related supplier evaluation index systems, few studies have discussed the problem of ferry operator evaluation from a sustainable perspective. Sustainability refers to the harmonious development of the economy, society, and the environment, and the concept has gained attention in many fields. Sustainability plays an important role in the economy, society and the environment. For example, some old ships emit too much carbon dioxide to pollute the ecological environment, and ferry operators with weak operating capabilities may have poor service capabilities and affect tourist satisfaction. Hence, this paper contributes to the ferry industry by selecting suitable ferry operators from a sustainability perspective. Economic, social and environmental criteria, thus, should be included at the very least in the construction of ferry operator evaluation index system. Besides, flexibility and management criteria are also crucial for ferry operator evaluation. In order to further reduce the influence of experts with different knowledge backgrounds and practical experience, five experts from the economic, university and environmental fields were invited to form a decision-making committee. The specific experts' information is shown in Table 3. Experts determined the evaluation criteria system through relevant literature analysis and interviews with ferry operators. Thus, evaluation indicator system of ferry operator herein should include environmental, economic, social, flexibility, and management criteria, as shown in Figure 2.

Table 3. Information for evaluation experts.

Experts	Fields	Age	Education	Work Experience	Professional Title	Experts' Weight
E1	Economy	60	Ph. D.	36	Senior engineer	0.25
E2	Economy	39	Master	17	Engineer	0.15
E3	College	56	Ph. D.	30	Professor	0.25
E4	College	43	Ph. D.	15	Assistant professor	0.15
E5	Environment	57	Master	35	Senior engineer	0.2

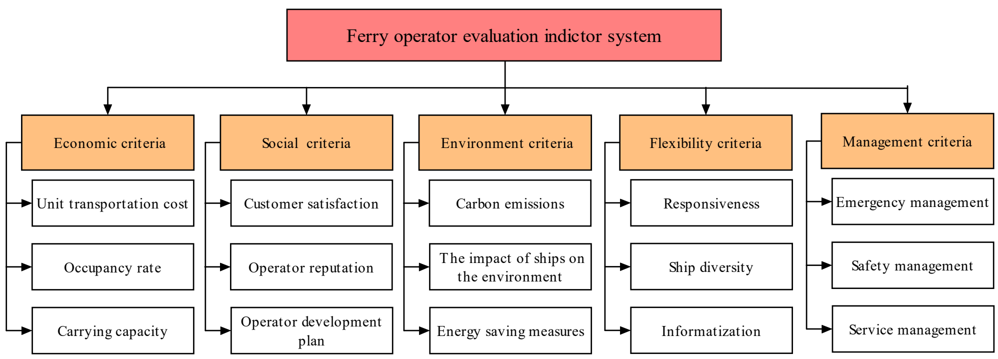

Figure 2. Ferry operator evaluation index system.

4.1. Social Criteria (C1)

Customer satisfaction (C11): Customer satisfaction usually refers to the customer's evaluation of the ferry operator's service, and a sustainable ferry operator should have high customer satisfaction.

Operator reputation (C12): A good reputation is a unique resource owned by an enterprise, which can enhance the competitiveness of the enterprise in all aspects of its operation. For any enterprise committed to long-term sustainable development, it is of great significance to strengthen corporate reputation management, so that the reputation of ferry operators can be effectively cultivated, accumulated, and maintained.

Operator development plan (C13): According to the objective actual situation of the enterprise itself and the environment, it is very important to analyze and formulate the development strategy plan of ferry operators, which is very important to promote the sustainable development of ferry operators.

4.2. Flexibility Criteria (C2)

Responsiveness (C21): Responsiveness is primarily the ability of a ferry operator to respond and handle in an emergency; for example, whether ferry operators can respond quickly to relieve transportation pressure when encountering heavy traffic. This criterion is crucial in measuring the flexibility of ferry operators.

Ship diversity (C22): Ship diversity refers to the types of ship available to ferry operators, such as comfort, economy, and high speed ship.

Informatization (C23): Informatization refers to the degree to which ferry operators use information technology. Informatization means that information technology is highly applied and information resources are highly shared, thus enabling ferry operators to deliver information quickly and accurately.

4.3. Economic Criteria (C3)

Unit transportation cost (C31): The operating cost per nautical mile is the value obtained by dividing the sum of the ferry operator's direct input costs and business taxes, etc., by the total mileage traveled. The direct input costs include fuel costs, employee wages, and ship depreciation costs. This criterion is a cost type, and the smaller the value, the better.

Occupancy rate (C32): Occupancy rate refers to the ratio of the total number of customers to the number of seats provided by the ferry operator.

Carrying capacity (C33): Carrying capacity refers to the ability of a ferry operator to transport tourists. Ferry operators with greater carrying capacity may have an advantage in terms of cost.

4.4. Management Criteria (C4)

Emergency management (C41): Emergency management means that ferry operators take a series of necessary measures by establishing necessary response mechanisms, applying science, technology, planning and management, etc. means to protect the safety of life, health and property of the public; and related activities to promote sustainable social development.

Safety management (C42): Safety management only refers to the management and control of the state of people, objects, and the environment by ferry operators during the operation process, and timely investigation of potential safety hazards.

Service management (C43): Service management refers to the services provided by ferry operators to passengers in the course of operation. It is necessary to evaluate whether these service contents, service pricing, etc. are reasonable.

4.5. Environmental Criteria (C5)

Carbon emissions (C51): In order to promote environmental sustainability, it is especially important to consider carbon emissions as a criterion. For ferry operators, phasing out some ships with high carbon emissions is of great significance for promoting the improvement of the ecological environment.

The impact of ships on the environment (C52): Noise and vibration during ferry transportation, toxic waste at the bottom, SOx, NOx, and PM2.5, etc. may have a negative impact on the environment.

Energy saving measures (C53): Energy-saving measures taken by ferry operators in their operations, and whether management measures are in place to conserve energy for possible energy waste.

5. Case Study

This section aims to verify the effectiveness of the proposed method with a real case, and demonstrates the flexibility and robustness of the proposed ensemble framework through sensitivity analysis.

5.1. Case Description

Because the Zhuhai Wanshan Islands have many tourist attractions, they are favored by tourists. However, due to the cost of building bridges or tunnels between islands, ferry services are currently the main means of transport connecting these islands to the interior. In order to achieve sustainable ferry transport services, the Zhuhai Municipal Government has to select an optimal ferry operator among four potential alternatives. Suppose the four alternatives are $A = (A_1,\ A_2, A_3, A_4)$. The information of evaluation experts is shown in Table 3. The weights of experts in Table 3 are obtained in the following ways: first, obtain the personal data of five experts (such as professional knowledge background, educational background, practical experience, etc.); then five local authority managers give each expert weight according to the expert data; and finally calculate their mean.

5.2. Criteria Weight

In order to clearly show the visual calculation process of the proposed method, we will give the calculation steps of the criteria weights.

5.2.1. Determine Subjective Criteria Weight by FAHP

Construct a pairwise fuzzy comparison matrix. According to the linguistic terms in Table 1, experts give evaluation results for the criteria and sub-criteria, and the evaluation results are shown in Tables A1–A6 in Appendix A. After obtaining the expert's initial linguistic evaluations, we need to aggregate all expert fuzzy evaluations using Equation (1), the results are given in Tables 4–9. Then compute the fuzzy synthetic extent value of the i-th object by Equations (2)–(4), and determine the degree of possibility by Equation (5). Finally, we can obtain the subjective criteria weight by using Equations (6)–(8), and the results are listed in Table 10.

Table 4. Aggregate all expert evaluations regarding the criteria.

Criteria	Society (C_1)	Flexibility (C_2)	Economic (C_3)	Management (C_4)	Environment (C_5)
Society (C_1)	(1, 1, 1)	(1.03, 1.26, 1.65)	(0.66, 0.83, 1.28)	(0.53, 0.76, 1.4)	(0.56, 0.89, 1.23)
Flexibility (C_2)	(0.91, 1.15, 1.40)	(1, 1, 1)	(0.73, 0.87, 1.2)	(0.52, 0.71, 1.15)	(0.88, 1.38, 1.88)
Economic (C_3)	(0.98, 1.35, 1.73)	(0.9, 1.2, 1.5)	(1, 1, 1)	(1.03, 1.53, 2.03)	(0.88, 1.1, 1.36)
Management (C_4)	(1.10, 1.6, 2.10)	(0.98, 1.48, 1.98)	(0.52, 0.72, 1.22)	(1, 1, 1)	(0.67, 1, 1.6)
Environment (C_5)	(1.16, 1.52, 2.15)	(0.58, 0.85, 1.63)	(1.04, 1.33, 1.63)	(0.67, 1, 1.6)	(1, 1, 1)

Table 5. Aggregate all expert evaluation of social criteria.

Sub-Criteria	Customer Satisfaction (C_{11})	Operator Reputation (C_{12})	Operator Development Plan (C_{13})
Customer satisfaction (C_{11})	(1, 1, 1)	(0.67, 1.10, 1.80)	(0.73, 0.95, 1.60)
Operator reputation (C_{12})	(0.57, 0.93, 1.60)	(1, 1, 1)	(0.67, 1.08, 1.50)
Operator development plan (C_{13})	(0.70, 1.08, 1.45)	(0.87, 01.17, 1.80)	(1, 1, 1)

Table 6. Aggregate all expert evaluation of flexibility criteria.

Sub-Criteria	Responsiveness (C_{21})	Ship Diversity (C_{22})	Informatization (C_{23})
Responsiveness (C_{21})	(1, 1, 1)	(0.68, 1.1, 1.53)	(0.94, 1.28, 2.01)
Ship diversity (C_{22})	(0.77, 1.07, 1.7)	(1, 1, 1)	(1.17, 1.49, 2.05)
Informatization (C_{23})	(0.76, 1.02, 1.35)	(1.01, 1.35, 1.71)	(1, 1, 1)

Table 7. Aggregate all expert evaluation of economic criteria.

Sub-Criteria	Unit Transportation Cost (C_{31})	Occupancy Rate (C_{32})	Carrying Capacity (C_{33})
Unit transportation cost (C_{31})	(1, 1, 1)	(0.73, 1.1, 2)	(0.64, 0.95, 1.85)
Occupancy rate (C_{32})	(0.5, 0.93, 1.4)	(1, 1, 1)	(0.9, 1.4, 1.9)
Carrying capacity (C_{33})	(0.58, 1.08, 1.58)	(0.55, 0.77, 1.33)	(1, 1, 1)

Table 8. Aggregate all expert evaluation of management criteria.

Sub-Criteria	Emergency Management (C_{41})	Safety Management (C_{42})	Service Management (C_{43})
Emergency management (C_{41})	(1, 1, 1)	(0.6, 1, 1.8)	(1.03, 1.3, 1.85)
Safety management (C_{42})	(0.57, 1,1.7)	(1, 1, 1)	(1.06, 1.33, 1.67)
Service management (C_{43})	(1, 1.4, 1.8)	(0.68, 0.92, 1.18)	(1, 1, 1)

Table 9. Aggregate all expert evaluation of environmental criteria.

Sub-Criteria	Carbon Emissions (C_{51})	The Impact of Ships on Environment (C_{52})	Energy Saving Measures (C_{53})
Carbon emissions (C_{51})	(1, 1, 1)	(0.58, 0.83, 1.52)	(0.66, 1.05, 1.45)
The impact of ships on the environment (C_{52})	(0.83, 1.33, 1.83)	(1, 1, 1)	(0.68, 1, 1.55)
Energy saving measures (C_{53})	(0.93, 1.24, 1.85)	(0.68, 1, 1.58)	(1, 1, 1)

Table 10. Subjective weights calculated by FAHP method.

Criteria	Weight	Sub-Criteria	Local Weight	Global Weight
C1	0.1724	C11	0.3295	0.0568
		C12	0.3245	0.0560
		C13	0.3460	0.0597
C2	0.1839	C21	0.3288	0.0605
		C22	0.3468	0.0638
		C23	0.3244	0.0596
C3	0.2236	C31	0.3346	0.0748
		C32	0.3544	0.0792
		C33	0.3111	0.0696
C4	0.2114	C41	0.3321	0.0702
		C42	0.3350	0.0708
		C43	0.3329	0.0704
C5	0.2087	C51	0.3073	0.0641
		C52	0.3501	0.0731
		C53	0.3426	0.0715

5.2.2. Determine Objective Criteria Weight by EW Method

First, the experts analyze the performance of the alternatives' sub-criteria, and give linguistic evaluation information, see Appendix A, Table A7. Besides, the experts give the evaluation results of the criteria according to the performance of the alternative sub-criteria, and express them in the linguistic terms in Table 2, and the results are shown in Table A8 in Appendix A. Second, we use Equations (9)–(11) to aggregate all expert evaluation values and convert the fuzzy values to crisp values. Equation (12) is then used for normalization, and Equation (13) is used to determine the entropy value for each criterion. Finally, Equation (14) is used to determine the weights of criteria and sub-criteria, and the results are shown in Table 11.

Table 11. Objective weights calculated by EW method.

Criteria	Weight	Sub-Criteria	Local Weight	Global Weight
C1	0.2603	C11	0.3905	0.1017
		C12	0.346	0.0901
		C13	0.2635	0.0686
C2	0.1886	C21	0.3874	0.0731
		C22	0.27	0.0509
		C23	0.3426	0.0646
C3	0.1981	C31	0.3805	0.0754
		C32	0.3183	0.0631
		C33	0.3012	0.0596
C4	0.1651	C41	0.3818	0.0630
		C42	0.3308	0.0546
		C43	0.2874	0.0474
C5	0.1879	C51	0.2985	0.0561
		C52	0.2753	0.0517
		C53	0.4262	0.0801

5.2.3. Combine FAHP and EW Method

The criteria weights obtained by the FAHP and EW methods are shown in Tables 10 and 11, respectively. Use Equation (15) to determine the criteria final weights. In this paper, we take $\beta = 0.6$, that is, the decision maker's preference for weighted decision-making obtained by subjective methods is 0.6, and the preference for weighted decision-making obtained by objective methods is 0.4. Then the final weight results obtained in this paper are shown in Table 12.

Table 12. Subjective and objective weights calculated by FAHP and EW method.

β.	Criteria	Weight	Sub-Criteria	Local Weight	Global Weight
0.6	C1	0.2075	C11	0.3539	0.0735
			C12	0.3331	0.0691
			C13	0.3130	0.0650
	C2	0.1858	C21	0.3522	0.0654
			C22	0.3160	0.0587
			C23	0.3317	0.0616
	C3	0.2134	C31	0.3530	0.0753
			C32	0.3400	0.0725
			C33	0.3071	0.0655
	C4	0.1929	C41	0.3520	0.0679
			C42	0.3333	0.0643
			C43	0.3147	0.0607
	C5	0.2004	C51	0.3038	0.0609
			C52	0.3202	0.0642
			C53	0.3760	0.0754

5.3. Determine the Alternative Rankings by Fuzzy TOPSIS

First, calculate the weighted evaluation information of all experts for the alternatives in Table A7. The quantitative data is processed as follows, taking C11 as an example, (0.93, 0.96, 0.94, 0.98), normalized to $\left(\frac{0.93}{0.98}, \frac{0.96}{0.98}, \frac{0.94}{0.98}, \frac{0.98}{0.98}\right) = (0.949,\ 0.9796,\ 0.9592, 1)$, then calculate their weighted values $0.0735 * (0.949,\ 0.9796,\ 0.9592, 1) = (0.07,\ 0.072,\ 0.071,\ 0.074)$. Use Equation (17) to normalize the fuzzy matrix; then calculate the weighted normalization matrix by using Equation (19); the fuzzy matrix can be defuzzified by Equation (20), and the results are shown in Table 13. The positive and negative ideal solutions are determined using Equation (21) for the clear values in Table 13, and the distance to the positive and negative ideal solutions for each alternative is determined by Equation (22). Finally, Equation (13) is used to calculate the closeness coefficient of each alternative, and the related results are shown in Table 14. We get the final ranking of the alternatives as $A_1 > A_3 > A_4 > A_2$ from Table 14; thus, alternative A_1 is the best ferry operator.

Table 13. Converting fuzzy evaluation values to crisp values.

Ai	C11	C12	C13	C21	C22	C23	C31	C32	C33	C41	C42	C43	C51	C52	C53
A1	0.070	0.050	0.052	0.054	0.041	0.036	0.069	0.073	0.048	0.049	0.052	0.049	0.008	0.022	0.059
A2	0.072	0.060	0.045	0.046	0.046	0.028	0.072	0.068	0.028	0.037	0.046	0.038	0.008	0.027	0.061
A3	0.071	0.045	0.050	0.044	0.044	0.050	0.066	0.062	0.044	0.054	0.041	0.046	0.006	0.039	0.054
A4	0.074	0.055	0.051	0.047	0.047	0.035	0.075	0.071	0.051	0.042	0.033	0.045	0.014	0.028	0.053

Table 14. Ferry operator's best alternative.

Ai	A_1	A_2	A_3	A_4
d_i^+	0.0004	0.0016	0.0009	0.0010
d_i^-	0.0017	0.0007	0.0013	0.0011
S_i	0.8113	0.3026	0.5789	0.5023
Ranking	1	4	2	3

5.4. Sensitive Analysis

In order to explore the impact of sub-criteria weight changes on decision-making results, sensitivity analysis of sub-criteria is required. In this paper, the weight of each sub-criterion is reduced by 30%, 20%, and 10% from the initial weight, and increased by 10%, 20%, and 30% from the initial weight, respectively. Figure 3 clearly shows that the change of the criteria weight has little effect on the quantitative criteria C11, C31 and C32, because the quantitative criteria evaluation given by all experts is the same. When the weight changes, the change of the weighted evaluation information value is not much different, so it will not have a great influence on the decision result. As the weight of C12 increases, the results of alternative A2 increase significantly, which means that of all the alternatives, A2 does the best in terms of the performance of C12. Furthermore, it is evident from Figure 3 that all the criteria of alternative A1 are less affected by the weight change, because the performance of all the criteria of A1 is more stable. Although the criteria weight change affects the evaluation results, it can be seen from Figure 3 that no matter how the criteria weight changes, the optimal alternative is still A1, which shows the reliability and robustness of the proposed method.

Next, we analyze the influence of decision makers' choice of subjective weight decision preference β on the results. We assume that β varies from 0 to 1 on 0.1 intervals, respectively. As can be seen from Figure 4, the result of alternative A1 increases as β increases, while the result of alternative A2 decreases as β increases. The results for alternative A4 did not change significantly.

5.5. Management Recommendations

An excellent sustainable ferry operator can have a vital impact on the ferry transport industry. However, there has not been a single literature report on the evaluation of ferry operators. Therefore, this paper studies the evaluation of ferry operators from the perspective of sustainability. We provide important management implications for the problems and findings in the research and provide reference for relevant stakeholders.

(1) For decision makers, how to choose the decision preference parameter β is still an important issue. Because decision parameter β has an impact on the outcome, how to reduce the risk of decision failure due to inconsistent decision preference parameters requires further scrutiny. The decision maker can consider the best alternative that

has little effect on the outcome due to changes in the decision preference parameter β, because the most criteria performance of the best alternative is superior. The criteria performance of an alternative where weight changes have a large impact on the results can vary widely, and it is not recommended to choose such an alternative.

(2) Regarding the evaluation index system of ferry operators, this paper constructs 5 criteria and 15 sub-criteria from the perspective of relevant literature and expert opinions. Since there are no previous literature reports on ferry operator evaluations, our criteria system may need to be justified in future studies.

(3) In the MCDM approach, since experts have ambiguity about the criteria assessment, reducing this ambiguity will reduce the risk of failing to select the best ferry operator.

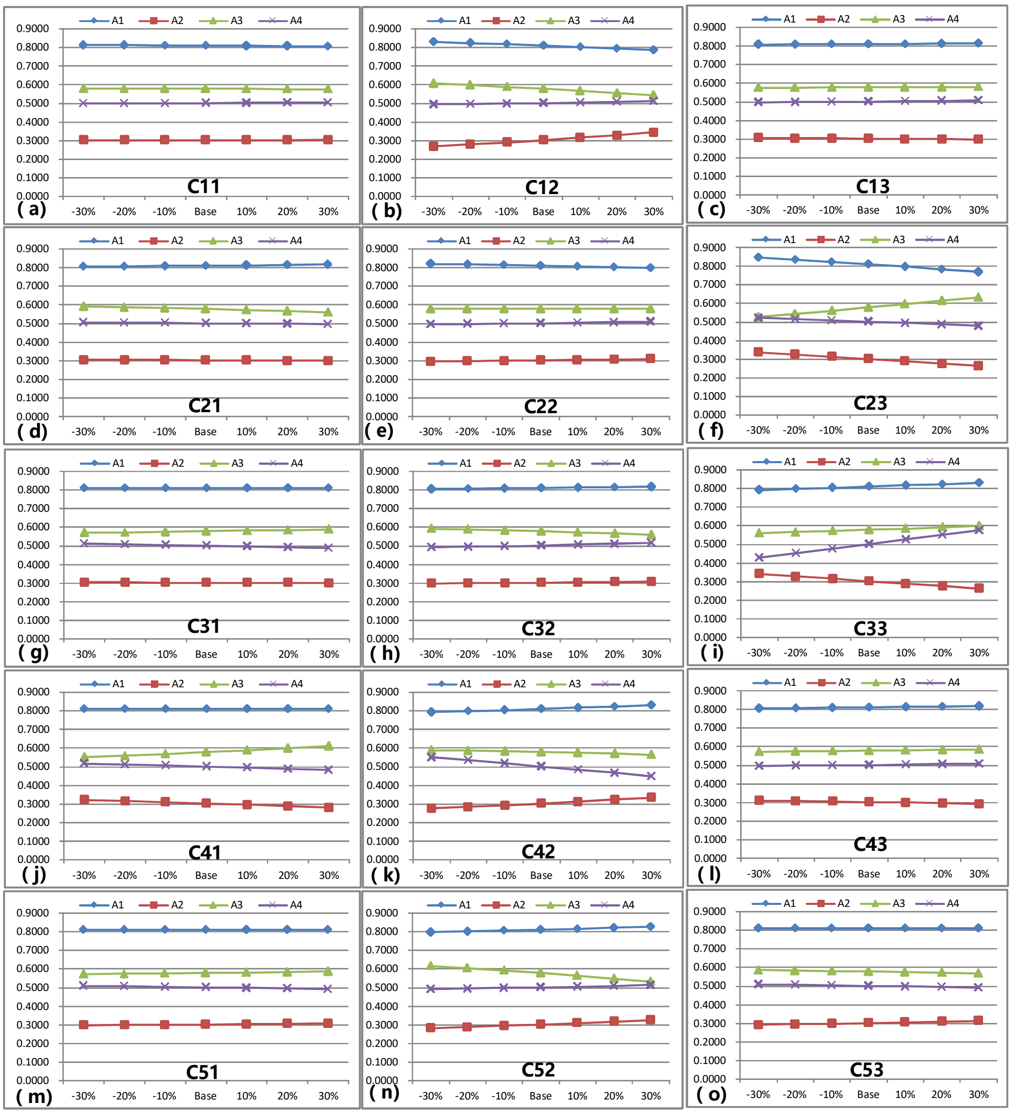

Figure 3. Sensitivity analysis result of sub-criteria (**a**–**o**).

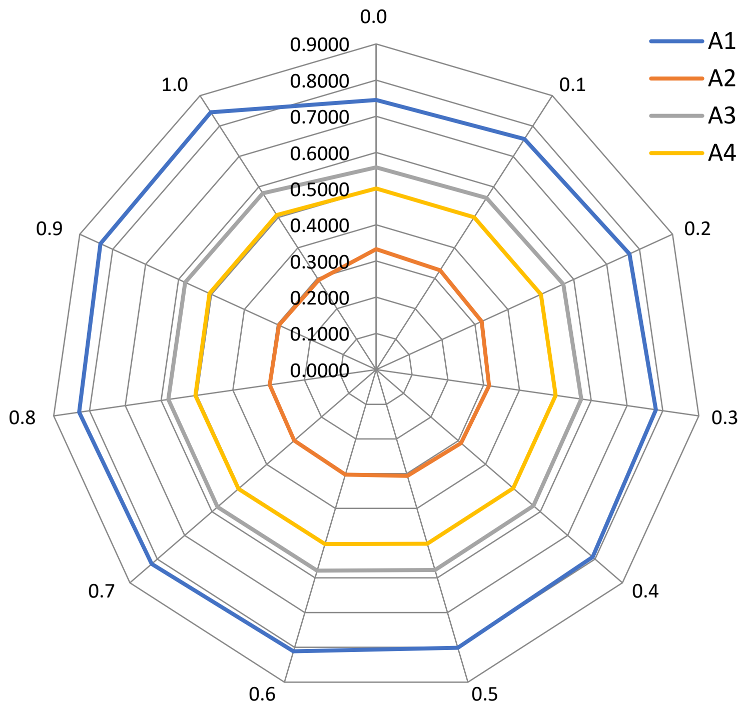

Figure 4. Sensitivity analysis result of β.

6. Conclusions

Selecting a sustainable ferry operator is beneficial both for the Zhuhai Municipal Government and for the ferry transport industry. Ferry operator evaluation is a complex scientific decision-making issue for authorities, as it often involves numerous potentially conflicting qualitative and quantitative criteria. Meanwhile, in the decision-making process, it is also necessary to consider the possible impact of experts with different knowledge backgrounds and practical experience on the evaluation. In addition, there may be ambiguity and uncertainty in expert assessments of criteria, and describing such ambiguity and uncertainty is inherently difficult. To this end, this paper proposes an integrated framework combining FAHP, EW method, and fuzzy TOPSISI technique to solve the evaluation and selection of ferry operators. First, the FAHP method is used to determine the subjective weight of the criteria, then the EW method is used to calculate the objective weight of the criteria, and finally the fuzzy TOPSIS method is used to rank the alternatives and obtain the best alternative. A real case is used to verify the effectiveness and robustness of the proposed method.

Considering the complexity of reality, in future research, we can adopt other MCDM techniques to evaluate and select ferry operators. For example, fuzzy axiomatic design, fuzzy VIKOR, or fuzzy ELECTRE, etc. each has own advantages, which may affect the results. It is worth noting that with the complexity of the future environment, it may be necessary to rebuild a new evaluation index system for sustainable ferry operators, and the corresponding weights may also be different. In future research, attempting to apply optimal modeling techniques to select ferry operators may be a research topic worth exploring.

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Appendix A

Table A1. The comparison result of the importance of criteria.

Criteria	Experts	Social (C_1)	Flexibility (C_2)	Economic (C_3)	Management (C_4)	Environment (C_5)
	E_1		(2, 5/2, 3)	(1, 1, 1)	(1/3, 2/5, 1/2)	(1/3, 2/5, 1/2)
	E_2		(1, 1, 1)	(2/3, 1, 2)	(2/3, 1, 2)	(1/3, 2/5, 1/2)
Social (C_1)	E_3	(1, 1, 1)	(2/3, 1, 2)	(2/3, 1, 2)	(2/3, 1, 2)	(1, 3/2, 2)
	E_4		(1, 1, 1)	(2/5, 1/2, 2/3)	(1/3, 2/5, 1/2)	(1/2, 1, 3/2)
	E_5		(1/3, 2/5, 1/2)	(2/5, 1/2, 2/3)	(2/3, 1, 2)	(1/2, 1, 3/2)
	E_1	(1/3, 2/5, 1/2)		(1/2, 2/3, 1)	(1/2, 2/3, 1)	(2, 5/2, 3)
	E_2	(1, 1, 1)		(1/2, 2/3, 1)	(1/2, 2/3, 1)	(1/2, 1, 3/2)
Flexibility (C_2)	E_3	(1/2, 1, 3/2)	(1, 1, 1)	(1, 1, 1)	(1/2, 2/3, 1)	(1/2, 1, 3/2)
	E_4	(1,1,1)		(1, 1, 1)	(2/5, 1/2, 2/3)	(1/2, 1, 3/2)
	E_5	(2, 5/2, 3)		(2/3, 1, 2)	(2/3, 1, 2)	(1/2, 1, 3/2)
	E_1	(1, 1, 1)	(1, 3/2, 2)		(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
	E_2	(1/2, 1, 3/2)	(1, 3/2, 2)		(3/2, 2, 5/2)	(1, 1, 1)
Economic (C_3)	E_3	(1/2, 1, 3/2)	(1, 1, 1)	(1, 1, 1)	(1, 3/2, 2)	(2/5, 1/2, 2/3)
	E_4	(3/2, 2, 5/2)	(1, 1, 1)		(1/2, 1, 3/2)	(3/2, 2, 5/2)
	E_5	(3/2, 2, 5/2)	(1/2, 1, 3/2)		(1/2, 1, 3/2)	(3/2, 2, 5/2)
	E_1	(2, 5/2, 3)	(1, 3/2, 2)	(2/5, 1/2, 2/3)		(2/3, 1, 2)
	E_2	(1/2, 1, 3/2)	(1, 3/2, 2)	(2/5, 1/2, 2/3)		(2/3, 1, 2)
Management (C_4)	E_3	(1/2, 1, 3/2)	(1, 3/2, 2)	(1/2, 2/3, 1)	(1, 1, 1)	(1/2, 1, 3/2)
	E_4	(2, 5/2, 3)	(3/2, 2, 5/2)	(2/3, 1, 2)		(1/2, 1, 3/2)
	E_5	(1/2, 1, 3/2)	(1/2, 1, 3/2)	(2/3, 1, 2)		(1, 1, 1)
	E_1	(2, 5/2, 3)	(1/3, 2/5, 1/2)	(3/2, 2, 5/2)	(1/2, 1, 3/2)	
	E_2	(2, 5/2, 3)	(2/3, 1, 2)	(1, 1, 1)	(1/2, 1, 3/2)	
Environment (C_5)	E_3	(1/2, 2/3, 1)	(2/3, 1, 2)	(3/2, 2, 5/2)	(2/3, 1, 2)	(1, 1, 1)
	E_4	(2/3, 1, 2)	(2/3, 1, 2)	(2/5, 1/2, 2/3)	(2/3, 1, 2)	
	E_5	(2/3, 1, 2)	(2/3, 1, 2)	(2/5, 1/2, 2/3)	(1, 1, 1)	

Table A2. Fuzzy pairwise comparison matrix on social criteria (C1).

Sub-Criteria	Experts	Customer Satisfaction (C_{11})	Operator Reputation (C_{12})	Operator Development Plan (C_{13})
	E_1		(1/2, 1, 3/2)	(1, 1, 1)
	E_2		(1/2, 1, 3/2)	(2/3, 1, 2)
Customer satisfaction (C_{11})	E_3	(1, 1, 1)	(2/3, 1, 2)	(2/3, 1, 2)
	E_4		(2/3, 1, 2)	(1/2, 2/3, 1)
	E_5		(1, 3/2, 2)	(2/3, 1, 2)
	E_1	(2/3, 1,2)		(1/2, 1, 3/2)
	E_2	(2/3, 1, 2)		(1/2, 1, 3/2)
Operator reputation (C_{12})	E_3	(1/2, 1, 3/2)	(1, 1, 1)	(1, 3/2, 2)
	E_4	(1/2, 1, 3/2)		(1, 3/2, 2)
	E_5	(1/2, 2/3, 1)		(1/3, 2/5, 1/2)
	E_1	(1, 1, 1)	(2/3, 1, 2)	
	E_2	(1/2, 1, 3/2)	(2/3, 1, 2)	
Operator development plan (C_{13})	E_3	(1/2, 1, 3/2)	(1/2, 2/3, 1)	(1, 1, 1)
	E_4	(1, 3/2, 2)	(1/2, 2/3, 1)	
	E_5	(1/2, 1, 3/2)	(2, 5/2, 3)	

Table A3. Fuzzy pairwise comparison matrix on flexibility criteria (C2).

Sub-Criteria	Experts	Responsiveness (C_{21})	Ship Diversity (C_{22})	Informatization (C_{23})
Responsiveness (C_{21})	E_1	(1, 1, 1)	(1, 3/2, 2)	(2/3, 1, 2)
	E_2		(1, 3/2, 2)	(2/3, 1, 2)
	E_3		(1/2, 1, 3/2)	(2, 5/2, 3)
	E_4		(1/2, 1, 3/2)	(2/7, 1/3, 2/5)
	E_5		(2/5, 1/2, 2/3)	(2/3, 1, 2)
Ship diversity (C_{22})	E_1	(1/2, 2/3, 1)	(1, 1, 1)	(2/3, 1, 2)
	E_2	(1/2, 2/3, 1)		(1/2, 2/3, 1)
	E_3	(2/3, 1, 2)		(1/2, 2/3, 1)
	E_4	(2/3, 1, 2)		(2, 5/2, 3)
	E_5	(3/2, 2, 5/2)		(5/2, 3, 7/2)
Informatization (C_{23})	E_1	(1/2, 2/3, 1)	(2, 5/2, 3)	(1, 1, 1)
	E_2	(1/2, 2/3, 1)	(1, 3/2, 2)	
	E_3	(1/3, 2/5, 1/2)	(1, 3/2, 2)	
	E_4	(5/2, 3, 7/2)	(1/3, 2/5, 1/2)	
	E_5	(1/2, 1, 3/2)	(2/7, 1/3, 2/5)	

Table A4. Fuzzy pairwise comparison matrix on economic criteria (C3).

Sub-Criteria	Experts	Unit Transportation Cost (C_{31})	Occupancy Rate (C_{32})	Carrying Capacity (C_{33})
Unit transportation cost (C_{31})	E_1	(1, 1, 1)	(2/3, 1, 2)	(2/3,1, 2)
	E_2		(2/3, 1, 2)	(2/3,1, 2)
	E_3		(2/3, 1, 2)	(2/3, 1, 2)
	E_4		(2/3, 1, 2)	(1/2, 2/3, 1)
	E_5		(1, 3/2, 2)	(2/3, 1, 2)
Occupancy rate (C_{32})	E_1	(1/2, 1, 3/2)	(1, 1, 1)	(1/2, 1, 3/2)
	E_2	(1/2, 1, 3/2)		(1/2, 1, 3/2)
	E_3	(1/2, 1, 3/2)		(1, 3/2, 2)
	E_4	(1/2, 1, 3/2)		(1, 3/2, 2)
	E_5	(1/2, 2/3, 1)		(3/2, 2, 5/2)
Carrying capacity (C_{33})	E_1	(1/2, 1, 3/2)	(2/3, 1, 2)	(1, 1, 1)
	E_2	(1/2, 1, 3/2)	(2/3, 1, 2)	
	E_3	(1/2, 1, 3/2)	(1/2, 2/3, 1)	
	E_4	(1, 3/2, 2)	(1/2, 2/3, 1)	
	E_5	(1/2, 1, 3/2)	(2/5, 1/2, 2/3)	

Table A5. Fuzzy pairwise comparison matrix on management criteria (C4).

Sub-Criteria	Experts	Emergency Management (C_{41})	Safety Management (C_{42})	Service Management (C_{43})
Emergency management (C_{41})	E_1	(1, 1, 1)	(1/2, 1, 3/2)	(2, 5/2, 3)
	E_2		(1/2, 1, 3/2)	(2/5, 1/2, 2/3)
	E_3		(2/3, 1, 2)	(2/3, 1, 2)
	E_4		(2/3, 1, 2)	(2/3, 1, 2)
	E_5		(2/3, 1, 2)	(1, 1, 1)
Safety management (C_{42})	E_1	(2/3, 1, 2)	(1, 1, 1)	(2/5, 1/2, 2/3)
	E_2	(2/3, 1, 2)		(2/5, 1/2, 2/3)
	E_3	(1/2, 1, 3/2)		(2, 5/2, 3)
	E_4	(1/2, 1, 3/2)		(2, 5/2, 3)
	E_5	(1/2, 1, 3/2)		(1/2, 2/3, 1)
Service management (C_{43})	E_1	(3/2, 2, 5/2)	(1/3, 2/5, 1/2)	(1, 1, 1)
	E_2	(3/2, 2, 5/2)	(3/2, 2, 5/2)	
	E_3	(1/2, 1, 3/2)	(1, 3/2, 2)	
	E_4	(1/2, 1, 3/2)	(1/3, 2/5, 1/2)	
	E_5	(1, 1, 1)	(1/3, 2/5, 1/2)	

Table A6. Fuzzy pairwise comparison matrix on environmental criteria (C5).

Sub-Criteria	Experts	Carbon Emissions (C_{51})	The Impact of Ships on the Environment (C_{52})	Energy Saving Measures (C_{53})
Carbon emissions (C_{51})	E_1	(1, 1, 1)	(2/3, 1, 2)	(1, 3/2, 2)
	E_2		(1/2, 2/3, 1)	(1, 3/2, 2)
	E_3		(2/5, 1/2, 2/3)	(1/3, 2/5, 1/2)
	E_4		(2/3, 1, 2)	(1/2, 1, 3/2)
	E_5		(2/3, 1, 2)	(1/2, 1, 3/2)
The impact of ships on the environment (C_{52})	E_1	(1/2, 1, 3/2)	(1, 1, 1)	(1, 1, 1)
	E_2	(1, 3/2, 2)		(1/2, 1, 3/2)
	E_3	(3/2, 2, 5/2)		(1/2, 1, 3/2)
	E_4	(1/2, 1, 3/2)		(2/3, 1, 2)
	E_5	(1/2, 1, 3/2)		(2/3, 1, 2)
Energy saving measures (C_{53})	E_1	(1/2, 2/3, 1)	(1, 1, 1)	(1, 1, 1)
	E_2	(1/2, 2/3, 1)	(2/3, 1, 2)	
	E_3	(2, 5/2, 3)	(2/3, 1, 2)	
	E_4	(2/3, 1, 2)	(1/2, 1, 3/2)	
	E_5	(2/3, 1, 2)	(1/2, 1, 3/2)	

Table A7. Alternative evaluation information.

Experts	Ai	C11	C12	C13	C21	C22	C23	C31	C32	C33	C41	C42	C43	C51	C52	C53
E1	A1	93%	H	VH	H	G	VH	359.57	62%	H	G	H	H	L	G	VH
	A2	96%	VH	G	H	H	L	342.48	58%	L	G	H	G	L	L	H
	A3	94%	VH	H	G	H	H	374.23	53%	H	H	G	H	G	VL	H
	A4	98%	H	H	VH	G	G	328.85	61%	H	G	L	H	VL	L	H
E2	A1	93%	H	H	H	G	G	359.57	62%	G	VH	G	VH	L	G	VH
	A2	96%	G	H	L	G	H	342.48	58%	L	L	VH	G	L	L	VH
	A3	94%	L	VH	G	G	VH	374.23	53%	G	H	G	G	L	G	H
	A4	98%	H	H	H	G	G	328.85	61%	H	L	H	H	VL	G	G
E3	A1	93%	VH	G	G	H	G	359.57	62%	G	G	H	H	L	VL	G
	A2	96%	VH	H	H	VH	L	342.48	58%	L	G	H	G	VL	L	H
	A3	94%	H	G	G	H	H	374.23	53%	L	H	H	G	G	VL	G
	A4	98%	VH	H	G	VH	G	328.85	61%	H	G	L	G	VL	VL	H
E4	A1	93%	G	VH	VH	G	L	359.57	62%	L	G	H	H	L	G	VH
	A2	96%	VH	G	G	H	L	342.48	58%	L	L	L	H	L	G	H
	A3	94%	G	G	G	G	H	374.23	53%	G	H	G	VH	L	VL	VH
	A4	98%	H	H	G	VH	L	328.85	61%	G	H	L	VH	VL	L	H
E5	A1	93%	G	G	VH	G	L	359.57	62%	VH	VH	VH	G	VL	G	G
	A2	96%	VH	G	H	L	G	342.48	58%	G	H	G	G	L	L	H
	A3	94%	G	H	VH	G	H	374.23	53%	H	H	G	H	VL	G	G
	A4	98%	H	G	G	G	H	328.85	61%	G	H	H	G	L	G	G

Table A8. Linguistic evaluation terms of criteria.

	Ai	C1	C2	C3	C4	C5		Ai	C1	C2	C3	C4	C5		Ai	C1	C2	C3	C4	C5
E1	A1	H	H	H	L	H	E2	A1	H	H	G	L	H	E3	A1	G	VH	G	VH	VH
	A2	H	G	VH	G	VH		A2	H	G	VH	H	L		A2	H	L	G	G	G
	A3	VH	H	G	G	H		A3	G	L	G	G	H		A3	G	H	G	VH	L
	A4	VH	G	H	G	G		A4	G	VH	H	H	G		A4	L	L	H	G	H
E4	A1	L	VH	G	H	VH	E5	A1	H	G	VH	H	VH							
	A2	G	H	G	H	G		A2	VH	L	G	H	G							
	A3	G	G	VL	H	L		A3	H	L	VH	G	G							
	A4	H	H	L	L	L		A4	G	VL	H	VH	VH							

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