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# An Offshore Wind–Wave Energy Station Location Analysis by a Novel Behavioral Dual-Side Spherical Fuzzy Approach: The Case Study of Vietnam

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**Abstract:** Despite the high capital requirements, offshore wind and wave energy integrated stations (WWS) are an emerging and potential solution to optimize efficiency in renewable energy development. Decisions about installation location significantly influence their efficiency. This study examines and determines highly efficient and sustainable locations based on quantitative indicators and qualitative criteria. For this purpose, a novel dual-side behavioral spherical fuzzy multi-criteria decision-making (MCDM) approach was developed and applied for the case study of Vietnam. In the first stage, the behavioral Data Envelopment Analysis (B-DEA) model, constructed based on prospect theory, is applied to analyze locations according to quantitative indicators under decision makers' psychological behavior consideration. In the second stage, a spherical fuzzy extension of the integration composed of the DEMATEL (decision-making trial and evaluation laboratory) and the EDAS (evaluation based on distance from average solution) methods helped to evaluate the locations. Based on the convergence in qualitative and quantitative analysis results, efficiency–sustainability positioning maps are established. The research provides recommendations for appropriate WWS locations from that visualization. The research compared findings with current development projects, plans, and policies in Vietnam for validation.

**Keywords:** wind energy; wave energy; renewable energy site section; multiple criteria decision making; fuzzy sets; Data Envelopment Analysis; prospect theory

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**Citation:** Le, M.-T.; Nhieu, N.-L. An Offshore Wind–Wave Energy Station Location Analysis by a Novel Behavioral Dual-Side Spherical Fuzzy Approach: The Case Study of Vietnam. *Appl. Sci.* **2022**, *12*, 5201. https://doi.org/10.3390/app12105201

Academic Editor: Yosoon Choi

Received: 23 April 2022
Accepted: 18 May 2022
Published: 20 May 2022



## 1. Introduction

To remove the dependence on fossil energy, the development of renewable energy has been emerging rapidly on a global scale. The onshore wind energy has reached technological maturity and is cost-effective [1]. However, onshore wind energy projects are limited by the disadvantages of land use, noise, and visible impacts. Therefore, the researchers and managers of renewables have gradually turned their attention to offshore projects [2]. Offshore wind power stations allow for the deployment of larger wind turbines and alleviate transport constraints. On the other hand, ocean energy studies are also developing at an early stage. Wave or tidal energy has great potential for development. Therefore, technologies that integrate offshore wind and wave energy are being developed vigorously [3]. In 2020, a good review about the future of offshore wind–wave integrated energy conversion systems was provided by Gao et al. The key finding of this study is the potential for greater energy generation and the reduced energy dispersion of integrated conversion systems [2].

Although WWSs are a solution to simultaneously exploit the wind and wave energy potential of the ocean, this type of integrated renewable energy is limited by high installation and operation and maintenance costs. Several attempts to optimize the cost of WWSs by the researchers have been found [4–6]. The primary purpose of integrated wind and wave energy studies is to minimize the cost and maximize the energy yield of offshore stations [7]. In addition to technological developments, determining the appropriate location is an important decision for the efficiency and sustainability of offshore wind and wave energy stations (WWS) [8,9]. Integrated multi-criteria decision-making (MCDM) approaches are increasingly being applied to the renewable energy site selection problems [8]. However, most renewable energy site selection studies use either expert-based assessments or quantitative analyses. In addition, decision-making processes are influenced by the psychological behavior of the decision maker, such as risk aversion, opinions on gains/losses [10]. Therefore, they leave an academic research gap for methods that combine expert-based assessment and quantitative assessment that consider psycho-behavior in the problem of location selection.

According to the International Energy Agency (IEA), Vietnam is leading the growth of renewable energy capacity of ASEAN with a contribution of 40% of renewable energy capacity [1]. Vietnam's wind power capacity is planned to share 1.5% in 2025 and 2.1% in 2030 of the total national electricity production [11]. World Bank studies forecast that Vietnam's offshore wind power will produce between 203 TWh and 433 TWh of electricity in 2035 [12]. However, offshore wind projects, either in the early stages or already in operation, are mostly nearshore wind power projects. Therefore, there is still a practical research gap on assessing suitable locations for offshore integrated wave and wind energy projects in Vietnam.

With the aim of narrowing the academic and practical research gaps discussed, the objective of this study is to analyze and evaluate the efficiency and sustainability of WWS locations in Vietnam. For this purpose, as theoretical contribution, this study proposes a novel behavioral dual-side spherical fuzzy approach. On the one side, the efficiency of WWS locations is evaluated based on quantitative indicators by a behavioral Data Envelopment Analysis (B-DEA) model, which is refined according to prospect theory principles. On the other side, the sustainability of locations is evaluated by an integrated MCDM method. The proposed MCDM method is composed of spherical fuzzy extensions of the DEMATEL method and EDAS method. Based on efficiency and sustainability rankings, this study classifies locations for WWS along the coastline of Vietnam as the practical contribution. In addition to the practical contribution of appropriate locations to WWSs, the remarkable novelty of this study is the novel behavioral dual-side spherical fuzzy approach for decision-support problems.

The remainder of this article includes the literature review in Section 2, the proposed methodology in Section 3, numerical results for Vietnam's WWS location selection in Section 4, and conclusions in Section 5.

## 2. Literature Review

First, this study provides an overview of the research available in the literature on site selection for renewable energy. Systematic review studies show that renewable energy selection studies are primarily directed towards a specific energy type dominated by solar and wind [8,9]. According to Table 1, MCDM methods are used in a variety, combined, and extended with fuzzy sets in the problem of location selection. However, site selection studies for integrated renewable energy are lacking. One of the related studies was site selection for a hybrid wind and solar energy system by Wu et al. [13], in which the analytic hierarchy process (AHP) method was applied to select the location of integrated renewable energy in China. In 2017, Vasileiou et al. used the AHP method in combination with geographic information system (GIS) to identify suitable locations for an integrated wind–wave energy project [14]. Recently, a study on the selection of wind and wave integrated energy locations in China's Hainan province was published by Zhou et al. [15]. This expert-based assessment is performed using a triangular fuzzy extension of the AHP method. In addition, several DEA-MCDM combinations for renewable energy site selection problems were found [16,17]. Besides the DEA method, different MCDM methods could be helpful.

For example, Peldschus et al. used the Game Theory to assess the construction site [18]. According to Karabasevic et al., the selection of project implementation sites highly depends on the available project implementation team [19] and available contractors [20], and feasible technologies [21]. Moreover, the alternative that is suitable to determine the local and international scopes and aims in a dynamically changing business environment [22] must protect nature and cultural heritage [23], which are requirements to turn to green energy. However, quantitative assessments that consider the psychological behavior of decision makers have not been found in the literature for this problem.

**Table 1.** MCDM application for renewable energy site selection problem.

| No. | Author | Year | Data Type | Approach | Energy Type | Applied Country |
|---|---|---|---|---|---|---|
| 1 | Karaaslan et al. [24] | 2021 | Crisp | AHP-MARCOS | Multiple | Turkey |
| 2 | Turk et al. [25] | 2021 | Intuitionistic fuzzy | AHP-TOPSIS | Photovoltaic solar | Turkey |
| 3 | Zambrano-Asanza et al. [26] | 2021 | Crisp | GIS-AHP-WLC | Photovoltaic solar | Ecuador |
| 4 | Bishnoi and Chaturvedi [27] | 2021 | Crisp | AHP-TOPSIS | Gas flaring renewable | India |
| 5 | Coruhlu et al. [28] | 2022 | Crisp | AHP-GIS | Solar | Turkey |
| 6 | Deveci et al. [29] | 2022 | q-rung Orthopair fuzzy | CoCoSo | Offshore wind | Norway |
| 7 | Emeksiz and Yüksel et al. [30] | 2022 | Crisp | MAUT-entropy | Bioenergy | Turkey |
| 8 | Gil-García et al. [31] | 2022 | Interval Fuzzy | GIS-AHP-TOPSIS | Offshore wind | USA |
| 9 | Noorollahi et al. [32] | 2022 | Multiple membership function | GIS-AHP | Photovoltaic solar | Iran |
| 10 | Zhou et al. [15] | 2022 | Triangular fuzzy | AHP-weighted overlay approach | Hybrid wind–wave | China |
| 11 | This study | 2022 | Spherical fuzzy | B-DEA and DEMATEL-EDAS | Hybrid wind–wave | Vietnam |

Note: MARCOS (measurement of alternatives and ranking according to compromise solution); TOPSIS (technique for order preference by similarity to ideal solution); WLC (weighted linear combination); CoCoSo (combined compromise solution); MAUT (multi-attribute utility theory); WOA (weighted overlay approach).

In practical terms, Vietnam is one of the leading countries in wind energy development in Southeast Asia [1]. At the same time, Vietnam has a coastline along the country. Therefore, Vietnam has great potential for offshore energy projects that take advantage of the inexhaustible energy sources of both wind and waves. However, no study on offshore wind and wave integrated energy has been found for the case of Vietnam. From the above review, it can be seen that there is a lack of studies on location selection for mixed renewable energy for Vietnam that apply both qualitative and quantitative analysis, including the psychological behavior of decision makers.

## 3. Methodology

In order to comprehensively evaluate and rank potential locations for WWSs, this study proposes a novel integrated decision-making approach consisting of two stages as illustrated in Figure 1. The objective of stage A is to evaluate the locations' efficiency based on quantitative indicators. These indicators contain information about energy potential, wave climate, bathymetry, distance to shore and so on. Based on the data of the indicators, a behavioral DEA model is used to determine the locations' efficiency under consideration of decision makers' psychosocial behavior. On the other hand, in stage B, the locations' sustainability is evaluated based on qualitative criteria. At this stage, a group of experts and evaluation criteria are determined. Then, the spherical fuzzy DEMATEL method is applied to calculate the weights of the evaluation criteria. In the next step, the locations' sustainability is evaluated according to the criteria using the spherical fuzzy EDAS method. Finally, the locations' ranking, discussions, and recommendations are provided based on both efficiency and sustainability assessments.

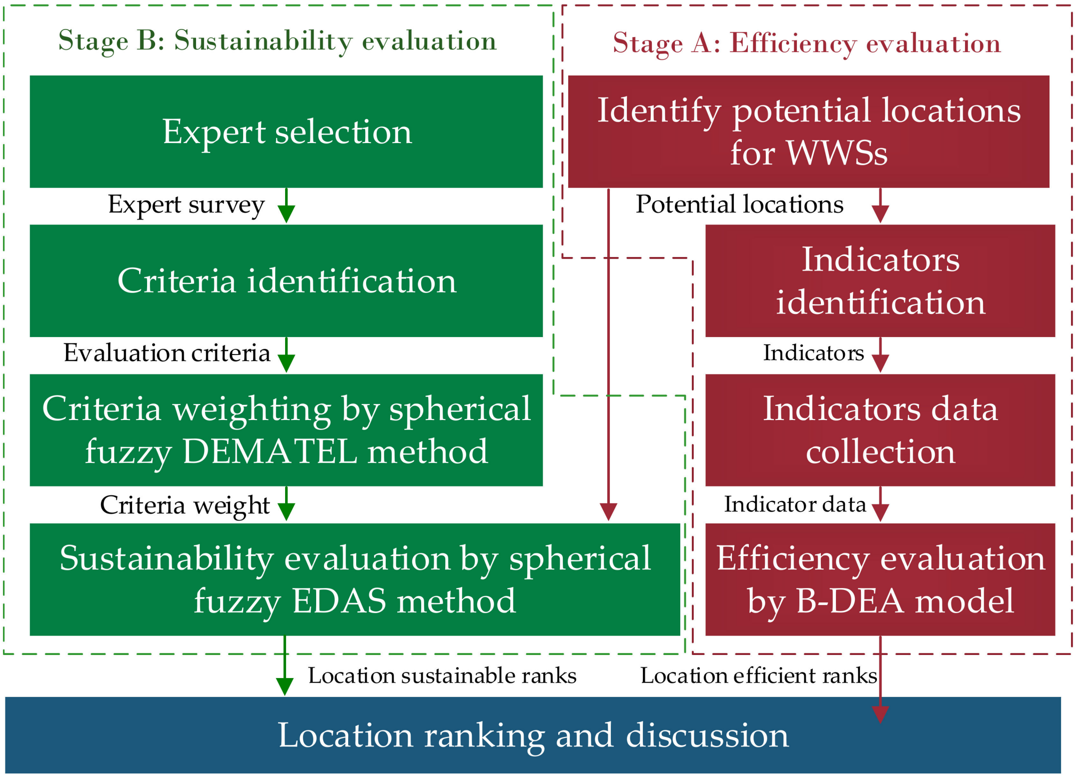


**Figure 1.** The proposed methodology.

*3.1. Behavioral Data Envelopment Analysis (B-DEA)*

In 1978, Charnes et al. introduced the primitive DEA model, referred to as the CCR model, to evaluate the technical efficiency of a decision-making unit (DMU) with the constant returns to scale assumption [33]. Because this assumption is unconvincing in many cases, the BCC model with the assumption of the variable returns to scale was proposed by Banker et al. [34]. Considering $M$ inputs $(i = 1 \ldots M)$ and $T$ outputs $(r = 1 \ldots T)$ of the $L$ DMUs $(j = 1 \ldots L)$, the technical efficiency $\psi_k$ of the $kth$ DMU can be calculated by solving the following model:

$$\begin{aligned} & maximize\ \psi_k = \phi + \sum_{r=1}^{T} u_r f_{rk} \\ subject\ to & \\ & \sum_{i=1}^{M} v_i e_{ik} = 1 \\ & \phi + \sum_{r=1}^{T} u_r f_{rj} - \sum_{i=1}^{M} v_i e_{ij} \le 0, \qquad j = 1, \ldots, L \\ & u_r,\ v_i \ge 0 \qquad\qquad i = 1, \ldots, M; r = 1, \ldots, T \\ & \phi \text{ is free} \end{aligned} \tag{1}$$

where $u_r$ and $v_i$ represent the weight of the $rth$ output and the $ith$ input, respectively. The $e_{ij}$ *and* $f_{rj}$ represent the $ith$ input value and $rth$ output value of $jth$ DMU. The $kth$ DMU is effective if the technical efficiency $(\psi_k)$ is 1.

Prospect theory is a descriptive theory for individual psychological behavior, which was introduced initially by Kahneman and Tversky [10]. Prospect theory is one of the widely applied theories in behavioral decision-making problems in many fields [35,36]. According to prospect theory, there are three important principles in behavioral decision-making as follows:

- Reference dependence: Individuals' perceptions of gains and losses depend on a reference point.

- Loss aversion: Individuals' sensitivity to losses is greater than to equal gains.
- Diminishing sensitivity: Individuals tend to be risk-seeking for losses and risk-averse for gains.

According to these three principles, the prospective value function is an asymmetrical S-shape curve as illustrated in Figure 2, in which the principle of reference dependence divides the prospect value function into a loss domain and a gain domain. On the other hand, the value function's slope of the gain domain is smaller than that of the loss domain according to the principle of loss aversion. In accordance with the principle of diminishing sensitivity, the prospect value function is convex in the gain domain and concave in the loss domain. The prospect value function is described in Equation (2).

$$f(\Delta t) = \begin{cases} (\Delta t)^{\alpha} & , \forall \Delta t \geq 0; 0 < \alpha < 1 \\ -\mu(-\Delta t)^{\beta} & , \forall \Delta t < 0; 0 < \beta < 1 \end{cases} \quad (2)$$

where $\Delta t$ represents the value of loss or gain relative to a reference point. The parameters $\mu$, $\alpha$, and $\beta$ represent the loss aversion, the gain risk attitude, and the loss risk attitude of decision makers, respectively.

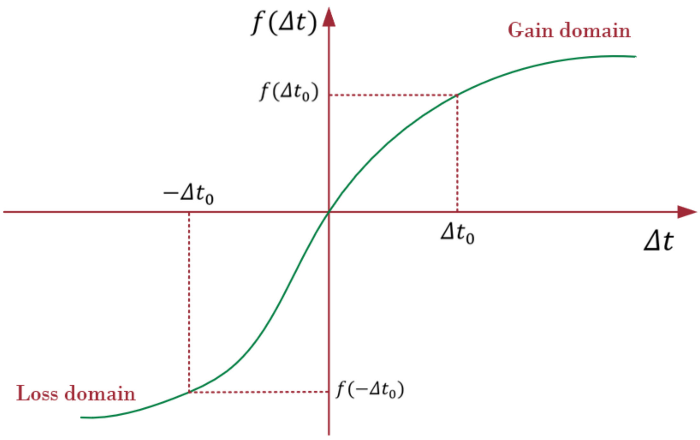


**Figure 2.** The prospect value function.

Based on prospect theory, Chen et al. proposed a new behavioral DEA model that includes the following steps [37]:

Step 1: The normalized value of input ($x_{ij}$) and output ($y_{ij}$) are determined as Equations (3) and (4).

$$x_{ij} = \frac{e_{ij}^{max} - e_{ij}}{e_{ij}^{max} - e_{ij}^{min}} \qquad j = 1, \ldots, L \quad (3)$$

$$y_{ij} = \frac{f_{ij} - f_{ij}^{min}}{f_{ij}^{max} - f_{ij}^{min}} \qquad j = 1, \ldots, L \quad (4)$$

Step 2: The positive and negative reference points are determined as Equations (5) and (6). The positive reference points ($e_i^+$ *and* $f_r^+$):

$$e_i^+ = \min_j(x_{ij}); f_r^+ = \max_r(y_{ij}) \quad (5)$$

The negative reference points ($e_i^-$ *and* $f_r^-$):

$$e_i^- = \max_j(x_{ij}); f_r^- = \min_r(y_{ij}) \quad (6)$$

Step 3: The Behavioral DEA model is constructed (7).

$$
\begin{aligned}
& maximize\ \varphi = \Theta\left(\phi + \sum_{r=1}^{T} u_{rk}\left(y_{rk} - f_r^-\right)^{\alpha} + \sum_{i=1}^{M} v_{ik}\left(e_i^- - x_{ik}\right)^{\alpha}\right) \\
& \qquad -(1-\Theta)\left(\phi + \sum_{r=1}^{T} u_{rk}\mu\left(f_r^+ - y_{rk}\right)^{\beta} + \sum_{i=1}^{M} v_{ik}\mu\left(x_{ik} - e_i^+\right)^{\beta}\right) \\
& subject\ to \\
& \qquad \sum_{i=1}^{M} v_{ik}e_{ik} = 1 \\
& \qquad \phi + \sum_{r=1}^{T} u_{rj}f_{rj} - \sum_{i=1}^{M} v_{ij}e_{ij} \le 0 \qquad j = 1,\ \ldots, L \\
& \qquad u_{rj},\ v_{ij} \ge 0 \qquad i = 1,\ \ldots, M; r = 1, \ldots, T; j = 1,\ \ldots, L \\
& \qquad \phi \text{ is free}
\end{aligned}
\tag{7}
$$

where $\Theta$ represents the relative degree of importance toward gains and $0 < \Theta < 1$. If $\Theta = 0.5$, it implies that the decision maker considers gains and losses equally important.

### 3.2. Spherical Fuzzy (SF) Sets

To deal with uncertainties in decision making, fuzzy sets have been introduced, evolved, and applied over the past decades as illustrated in Figure 3 [38–44]. The spherical fuzzy set, which was introduced recently, has attracted the attention of researchers [45–47]. The definition of SFS and its basic operators are presented as follows:

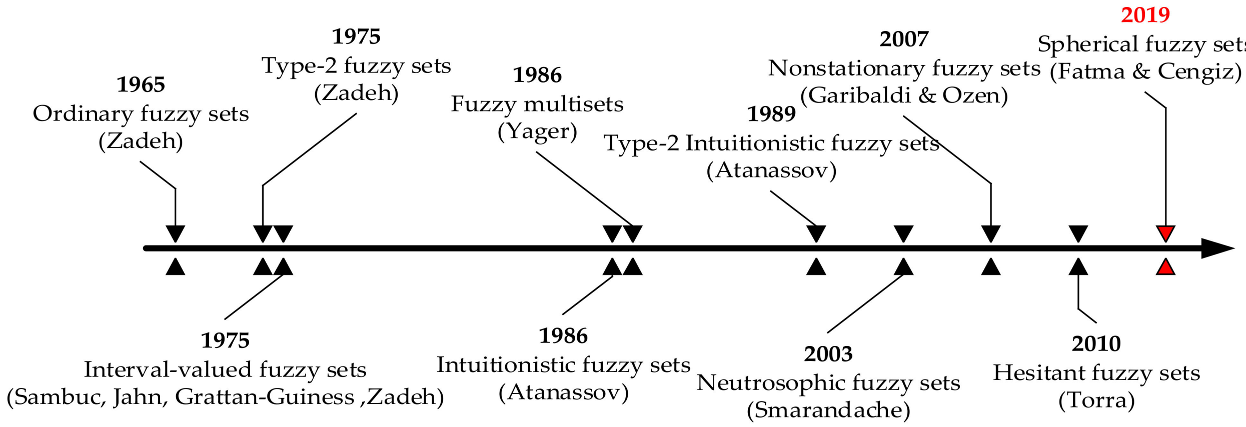


**Figure 3.** The fuzzy set development.

**Definition 1.** *Spherical fuzzy set $\widetilde{A}$ of the universe of discourse X is defined by*

$$\widetilde{A} = \left\{ \left\langle x, \left(\alpha_{\widetilde{A}}(x), \beta_{\widetilde{A}}(x), \gamma_{\widetilde{A}}(x)\right) \middle| x \in X \right\rangle \right\} \tag{8}$$

*where*

$$\alpha_{\widetilde{A}}, \beta_{\widetilde{A}},\ \gamma_{\widetilde{A}} : X \to [0,\ 1] \text{ and } 0 \le \alpha^2_{\widetilde{A}}(x) + \beta^2_{\widetilde{A}}(x) + \gamma^2_{\widetilde{A}}(x) \le 1 \qquad \forall x \in X \tag{9}$$

*The numbers $\alpha_{\widetilde{A}}(x), \beta_{\widetilde{A}}(x)$, and $\gamma_{\widetilde{A}}(x)$ are the membership degree, non-membership degree, and hesitancy degree of each x to $\widetilde{A}$, respectively.*

**Definition 2.** *Consider two universes $X_1$ and $X_2$. Let $\widetilde{A} = \left(\alpha_{\widetilde{A}}, \beta_{\widetilde{A}}, \gamma_{\widetilde{A}}\right)$ and $\widetilde{B} = \left(\alpha_{\widetilde{B}}, \beta_{\widetilde{B}}, \gamma_{\widetilde{B}}\right)$ be two spherical fuzzy sets (SFS) from the universe of discourse $X_1$ and $X_2$. The Basic operators are defined as follows:*

*Addition*

$$\widetilde{A} \oplus \widetilde{B} = \left\{ \left(\alpha^2_{\widetilde{A}} + \alpha^2_{\widetilde{A}} - \alpha^2_{\widetilde{A}}\alpha^2_{\widetilde{B}}\right)^{\frac{1}{2}}, \beta_{\widetilde{A}}\beta_{\widetilde{B}}, \left(\left(1 - \alpha^2_{\widetilde{B}}\right)\gamma^2_{\widetilde{A}} + \left(1 - \alpha^2_{\widetilde{A}}\right)\gamma^2_{\widetilde{B}} - \gamma^2_{\widetilde{A}}\gamma^2_{\widetilde{B}}\right)^{\frac{1}{2}} \right\} \tag{10}$$

*Multiplication*

$$\widetilde{A} \otimes \widetilde{B} = \left\{ \alpha_{\widetilde{A}}\alpha_{\widetilde{B}}, \left(\beta^2_{\widetilde{A}} + \beta^2_{\widetilde{B}} - \beta^2_{\widetilde{A}}\beta^2_{\widetilde{B}}\right)^{\frac{1}{2}}, \left(\left(1 - \beta^2_{\widetilde{B}}\right)\gamma^2_{\widetilde{A}} + \left(1 - \beta^2_{\widetilde{A}}\right)\gamma^2_{\widetilde{B}} - \gamma^2_{\widetilde{A}}\gamma^2_{\widetilde{B}}\right)^{\frac{1}{2}} \right\} \tag{11}$$

*Multiplication by a scalar* $(\lambda > 0)$

$$\lambda\widetilde{A} = \left\{ \left(1 - \left(1 - \alpha_{\widetilde{A}}^2\right)^{\lambda}\right)^{\frac{1}{2}}, \beta_{\widetilde{A}}^{\lambda}, \left(\left(1 - \alpha_{\widetilde{A}}^2\right)^{\lambda} - \left(1 - \alpha_{\widetilde{A}}^2 - \gamma_{\widetilde{A}}^2\right)^{\lambda}\right)^{\frac{1}{2}} \right\} \tag{12}$$

*Power of* $\widetilde{A}$ $(\lambda > 0)$

$$\widetilde{A}^{\lambda} = \left\{ \alpha_{\widetilde{A}}^{\lambda}, \left(1 - \left(1 - \beta_{\widetilde{A}}^2\right)^{\lambda}\right)^{\frac{1}{2}}, \left(\left(1 - \beta_{\widetilde{A}}^2\right)^{\lambda} - \left(1 - \beta_{\widetilde{A}}^2 - \gamma_{\widetilde{A}}^2\right)^{\lambda}\right)^{\frac{1}{2}} \right\} \tag{13}$$

**Definition 3.** *Consider the weight vector* $w = (w_1, w_2, \ldots, w_n)$*, where* $0 \leq w_i \leq 1$ *and* $\sum_{i=1}^{n} w_i = 1$*. Spherical weighted arithmetic mean (SWAM) and spherical weighted geometric mean (SWGM) are defined as follows:*

$$SWAM_w\left(\widetilde{A}_1, \widetilde{A}_2, \ldots, \widetilde{A}_n\right) = w_1\widetilde{A}_1 + w_2\widetilde{A}_2 + \ldots + w_n\widetilde{A}_n$$
$$= \left\{ \left(1 - \prod_{i=1}^{n}\left(1 - \alpha_{\widetilde{A}_i}^2\right)^{w_i}\right)^{\frac{1}{2}}, \prod_{i=1}^{n} \beta_{\widetilde{A}_i}^{w_i}, \left(\prod_{i=1}^{n}\left(1 - \alpha_{\widetilde{A}_i}^2\right)^{w_i} - \prod_{i=1}^{n}\left(1 - \alpha_{\widetilde{A}_i}^2 - \gamma_{\widetilde{A}_i}^2\right)^{w_i}\right)^{\frac{1}{2}} \right\} \tag{14}$$

$$SWGM_w\left(\widetilde{A}_1, \widetilde{A}_2, \ldots, \widetilde{A}_n\right) = \widetilde{A}_1^{w_1} + \widetilde{A}_2^{w_2} + \ldots + \widetilde{A}_n^{w_n}$$
$$= \left\{ \prod_{i=1}^{n} \alpha_{\widetilde{A}_i}^{w_i}, \left(1 - \prod_{i=1}^{n}\left(1 - \beta_{\widetilde{A}_i}^2\right)^{w_i}\right)^{\frac{1}{2}}, \left(\prod_{i=1}^{n}\left(1 - \beta_{\widetilde{A}_i}^2\right)^{w_i} - \prod_{i=1}^{n}\left(1 - \beta_{\widetilde{A}_i}^2 - \gamma_{\widetilde{A}_i}^2\right)^{w_i}\right)^{\frac{1}{2}} \right\} \tag{15}$$

**Definition 4** [45]. *Consider two universes* $X_1$ *and* $X_2$*. Let* $\widetilde{A} = \left(\alpha_{\widetilde{A}}, \beta_{\widetilde{A}}, \gamma_{\widetilde{A}}\right)$ *and* $\widetilde{B} = \left(\alpha_{\widetilde{B}}, \beta_{\widetilde{B}}, \gamma_{\widetilde{B}}\right)$ *be two SFSs from the universe of discourse* $X_1$ *and* $X_2$*. The followings are valid under the condition* $\lambda$, $\lambda_1$, $\lambda_2 > 0$.

$$\widetilde{A} \oplus \widetilde{B} = \widetilde{B} \oplus \widetilde{A} \tag{16}$$

$$\widetilde{A} \otimes \widetilde{B} = \widetilde{B} \otimes \widetilde{A} \tag{17}$$

$$\lambda\left(\widetilde{A} \oplus \widetilde{B}\right) = \lambda\widetilde{A} \oplus \lambda\widetilde{B} \tag{18}$$

$$\lambda_1\widetilde{A} \oplus \lambda_2\widetilde{A} = (\lambda_1 + \lambda_2)\widetilde{A} \tag{19}$$

$$\left(\widetilde{A} \otimes \widetilde{B}\right)^{\lambda} = \widetilde{A}^{\lambda} \otimes \widetilde{B}^{\lambda} \tag{20}$$

$$\widetilde{A}^{\lambda_1} \otimes \widetilde{A}^{\lambda_2} = \widetilde{A}^{\lambda_1 + \lambda_2} \tag{21}$$

**Definition 5.** *The defuzzied value (DFV) of SFS* $\widetilde{A} = \left(\alpha_{\widetilde{A}}, \beta_{\widetilde{A}}, \gamma_{\widetilde{A}}\right)$ *IS defined as follows:*

$$DFV\left(\widetilde{A}\right) = \left(\alpha_{\widetilde{A}} - \gamma_{\widetilde{A}}\right)^2 + \left(\beta_{\widetilde{A}} - \gamma_{\widetilde{A}}\right)^2 \tag{22}$$

### *3.3. Spherical Fuzzy DEMATEL-EDAS Method*

To evaluate the interrelationships of factors in complex systems, the DEMATEL method was initially proposed by Fontela and Gabus [48]. A systematic review of MCDM studies found that the DEMATEL method is increasingly used in the role of weighting criteria. In terms of prioritizing alternatives, distance-based evaluation methods, such as TOPSIS or EDAS, are applied effectively with high frequency [8]. Moreover, fuzzy variations of MCDM methods are introduced and proposed more and more widely. Therefore, this study proposes a spherical fuzzy extension of the integration approach composed by DEMATEL and EDAS, named SF DEMATEL–EDAS, for the first time. The proposed approach includes the following steps:

*Step 1: Identify experts and criteria*

In this step, a group of experts $(k = 1, 2, \ldots, K)$ with experience and a high level of expertise in the research field is selected. Then, the evaluation criteria $(j = 1, 2, \ldots, J)$ are determined according to previous studies and expert contributions.

*Step 2: Prioritize experts*

The weights of experts are calculated because of the difference in their experience, knowledge, and expertise level. Let the expertise of the $kth$ expert be expressed as a spherical fuzzy number (SFN) $\widetilde{A}_k = (\alpha_k, \beta_k, \gamma_k)$. The crisp weight of the $kth$ expert can be calculated as Equation (23) [49].

$$\vartheta_k = \frac{1-\sqrt{\left(\left(1-\alpha_k^2\right)+\beta_k^2+\gamma_k^2\right)/3}}{\sum_k\left(1-\sqrt{\left(\left(1-\alpha_k^2\right)+\beta_k^2+F\gamma_k^2\right)/3}\right)}$$
where
$$\sum_{k=1}^{K}\vartheta_k = 1 \tag{23}$$
and
$$0 \le \alpha_k^2 + \beta_k^2 + \gamma_k^2 \le 1$$

*Step 3: Construct the individual direct influence matrices*

The experts provide linguistic pairwise comparisons of the influence between the evaluation criteria. These linguistic pairwise comparisons were then converted to the respective SFNs as shown in Table 2 [50]. The individual direct influence matrix of the $kth$ expert is represented by $U^k = \left[\widetilde{u}_{jl}^k\right]_{JxJ} = \left[\left(\alpha_{jl}^k, \beta_{jl}^k, \gamma_{jl}^k\right)\right]_{JxJ}$.

**Table 2.** Linguistics term and respective SFNs for the SF DEMATEL method.

| Linguistics Term | Notation | Spherical Fuzzy Numbers |
|---|---|---|
| No Influence | NI | (0, 0.3, 0.2) |
| Weak Influence | WI | (0.35, 0.25, 0.25) |
| Moderate Influence | MI | (0.6, 0.2, 0.35) |
| Strong Influence | SI | (0.85, 0.15, 0.45) |

*Step 4: Construct the aggregated direct influence matrix*

The aggregated direct influence matrix is constructed by aggregating the matrices of the experts. This aggregation process applies the spherical weight arithmetic mean SWAM according to Equation (14). The aggregated direct influence matrix of the $kth$ expert is represented by $U^* = \left[\widetilde{u}_{jl}^*\right]_{JxJ} = \left[\left(\alpha_{jl}^*, \beta_{jl}^*, \gamma_{jl}^*\right)\right]_{JxJ}$.

*Step 5: Construct the initial direct influence submatrices*

To normalize the aggregated direct influence matrix, it is split into three submatrices corresponding to each parameter of the SFS. These submatrices are represented by $U^\alpha = \left[\alpha_{jl}^*\right]_{JxJ}$, $U^\beta = \left[\beta_{jl}^*\right]_{JxJ}$, and $U^\gamma = \left[\gamma_{jl}^*\right]_{JxJ}$. Then, the normalized submatrices are calculated as Equations (24)–(26).

$$V^\alpha = s^\alpha \times U^\alpha, \text{where } s^\alpha = min\left(\frac{1}{\max\limits_j \sum_{l=1}^{J}\alpha_{il}^*}, \frac{1}{\max\limits_l \sum_{j=1}^{J}\alpha_{il}^*}\right) \tag{24}$$

$$V^\beta = s^\beta \times U^\beta, \text{where } s^\beta = min\left(\frac{1}{\max\limits_j \sum_{l=1}^{J}\beta_{il}^*}, \frac{1}{\max\limits_l \sum_{j=1}^{J}\beta_{il}^*}\right) \tag{25}$$

$$V^\gamma = s^\gamma \times U^\gamma, \text{where } s^\gamma = min\left(\frac{1}{\max\limits_j \sum_{l=1}^{J}\gamma_{il}^*}, \frac{1}{\max\limits_l \sum_{j=1}^{J}\gamma_{il}^*}\right) \tag{26}$$

*Step 6: Construct the total direct influence matrix*

Firstly, the initial influence submatrices are transformed into total influence submatrices according to Equations (27)–(29) [51].

$$T^{\alpha} = V^{\alpha}(I - V^{\alpha})^{-1} \quad (27)$$

$$T^{\beta} = V^{\beta}\left(I - V^{\beta}\right)^{-1} \quad (28)$$

$$T^{\gamma} = V^{\gamma}(I - V^{\gamma})^{-1} \quad (29)$$

Next, the total influence submatrices are combined to form the total influence matrix, which is represented by $T = \left[\widetilde{t}_{jl}\right]_{JxJ} = \left[\left(\alpha^{T}_{jl}, \beta^{T}_{jl}, \gamma^{T}_{jl}\right)\right]_{JxJ}$.

*Step 7: Calculate the SF row and column sums*

In this step, the SF row sum $\left(\widetilde{r}_j\right)$ and the SF column sum $\left(\widetilde{c}_j\right)$ of the total influence matrix are computed according to Equations (30) and (31). The summing process utilizes the SF addition operator as shown in Equation (10).

$$\widetilde{r}_j = \sum_{l=1}^{J} \widetilde{t}_{jl} \qquad j = 1 \ldots J \quad (30)$$

$$\widetilde{c}_l = \sum_{j=1}^{J} \widetilde{t}_{jl} \qquad l = 1 \ldots J \quad (31)$$

*Step 8: Calculate the criteria' prominence, relation and weight*

First, the SF row sum $\left(\widetilde{r}_j\right)$ and the SF column sum $\left(\widetilde{c}_j\right)$ are defuzzied according to Equation (22). Based on the results of defuzzification, the prominence, the relation, and the weight $\left(w_j\right)$ of the $jth$ criteria are determined as follows:

$$prominence_j = r_j + c_j \qquad j = 1 \ldots J \quad (32)$$

$$relation_j = r_j - c_j \qquad j = 1 \ldots J \quad (33)$$

$$w_j = \frac{r_j + c_j}{\sum_{j=1}^{J}\left(r_j + c_j\right)} \qquad j = 1 \ldots J \quad (34)$$

*Step 9: Construct the spherical fuzzy decision matrix*

In this step, each expert provides the linguistic evaluation of alternatives $(i = 1, 2, \ldots, I)$ according to the criteria. Based on the relationships presented in Table 3, the linguistic evaluations are transformed into the corresponding SFNs. Using the SWAM, the SF decision matrix ($\widetilde{X} = \left[\widetilde{x}_{ij}\right]_{IxJ}$) is constructed as Equation (35).

$$\widetilde{x}_{ij} = SWAM_{\vartheta}\left(\widetilde{x}^{1}_{ij}, \widetilde{x}^{2}_{ij}, \ldots, \widetilde{x}^{k}_{ij}\right) = \vartheta_1 \widetilde{x}^{1}_{ij} + \vartheta_2 \widetilde{x}^{2}_{ij} + \ldots + \vartheta_k \widetilde{x}^{k}_{ij} \qquad i = 1 \ldots I; j = 1 \ldots J \quad (35)$$

**Table 3.** Linguistics term and respective SFNs for the SF EDAS method.

| Linguistics Term | Notation | Spherical Fuzzy Numbers |
|---|---|---|
| Absolutely Low | AL | (0.1, 0.9, 0.1) |
| Very Low | VL | (0.2, 0.8, 0.2) |
| Low | L | (0.3, 0.7, 0.3) |
| Slightly Low | SL | (0.4, 0.6, 0.4) |
| Medium | M | (0.5, 0.5, 0.5) |
| Slightly High | SH | (0.6, 0.4, 0.4) |
| High | H | (0.7, 0.3, 0.3) |
| Very High | VH | (0.8, 0.2, 0.2) |
| Absolutely High | AH | (0.9, 0.1, 0.1) |

*Step 10: Identify the spherical fuzzy average solution*

Based on the SF decision matrix, the SF average solution is determined by SWAM as Equation (34). The average solution represented by $\widetilde{AV} = [\widetilde{av}_j]_J$.

$$\widetilde{av}_j = SWAM(\widetilde{x}_{1j}, \widetilde{x}_{2j}, \ldots, \widetilde{x}_{Ij}) = \frac{1}{I}\widetilde{x}_{1j} + \frac{1}{I}\widetilde{x}_{2j} + \ldots + \frac{1}{I}\widetilde{x}_{Ij} \qquad j = 1 \ldots J \quad (36)$$

*Step 11: Identify the crisp decision matrix and the crisp average solution*

The crisp decision matrix and crisp average solution are constructed by defuzzification process according to Equation (22).

*Step 12: Identify the positive distance from average matrix and the negative distance from average matrix*

Based on the crisp decision matrix and the crisp average solution, the positive distance from average matrix $\left(PDA = \left[d_{ij}^{+}\right]_{IxJ}\right)$ and the negative distance from average matrix $\left(NDA = \left[d_{ij}^{-}\right]_{IxJ}\right)$ are defined as Equations (37) and (38).

$$d_{ij}^{+} = \frac{\max(0, x_{ij} - av_j)}{av_j} \quad (37)$$

$$d_{ij}^{-} = \frac{\max(0, av_j - x_{ij})}{av_j} \quad (38)$$

*Step 13: Calculate the weighted sum positive distance and the weighted sum negative distance*

In this step, the weighted sum positive distance $(s_i^{+})$ and the weighted sum negative distance $(s_i^{-})$ are computed as Equations (39) and (40), respectively, in which the criteria weights $(w_j)$ are determined in Step 8.

$$s_i^{+} = \sum_{j=1}^{J} w_j d_{ij}^{+} \quad (39)$$

$$s_i^{-} = \sum_{j=1}^{J} w_j d_{ij}^{-} \quad (40)$$

Next, the normalized weighted sum of positive distance $(ns_i^{+})$ and the normalized weighted sum of negative distance $(ns_i^{-})$ are determined as follows.

$$ns_i^{+} = \frac{s_i^{+}}{\max_i(s_i^{+})} \quad (41)$$

$$ns_i^{-} = 1 - \frac{s_i^{-}}{\max_i(s_i^{-})} \quad (42)$$

*Step 14: Calculate the alternatives' appraisal score*

Ultimately, the appraisal score $(as_i)$ of alternatives is calculated as Equation (43). The alternative with a larger appraisal score is better. In other words, the alternatives are ranked in descending order of the appraisal score.

$$as_i = \frac{1}{2}(ns_i^{+} + ns_i^{-}) \quad (43)$$

## 4. Case Study

### *4.1. Location Identification*

In this section, the proposed approach is applied to evaluate and select locations for WWS in Vietnam. After excluding military and conservation areas, this study considered twenty feasible locations along the coast, numbered in ascending order from north to south as illustrated in Figure 4. In addition, the distance to the shore of these locations was greater than 25 km to avoid negative impacts on other economic and social activities [14]. The locations' geographical coordinates are presented in Table A1.

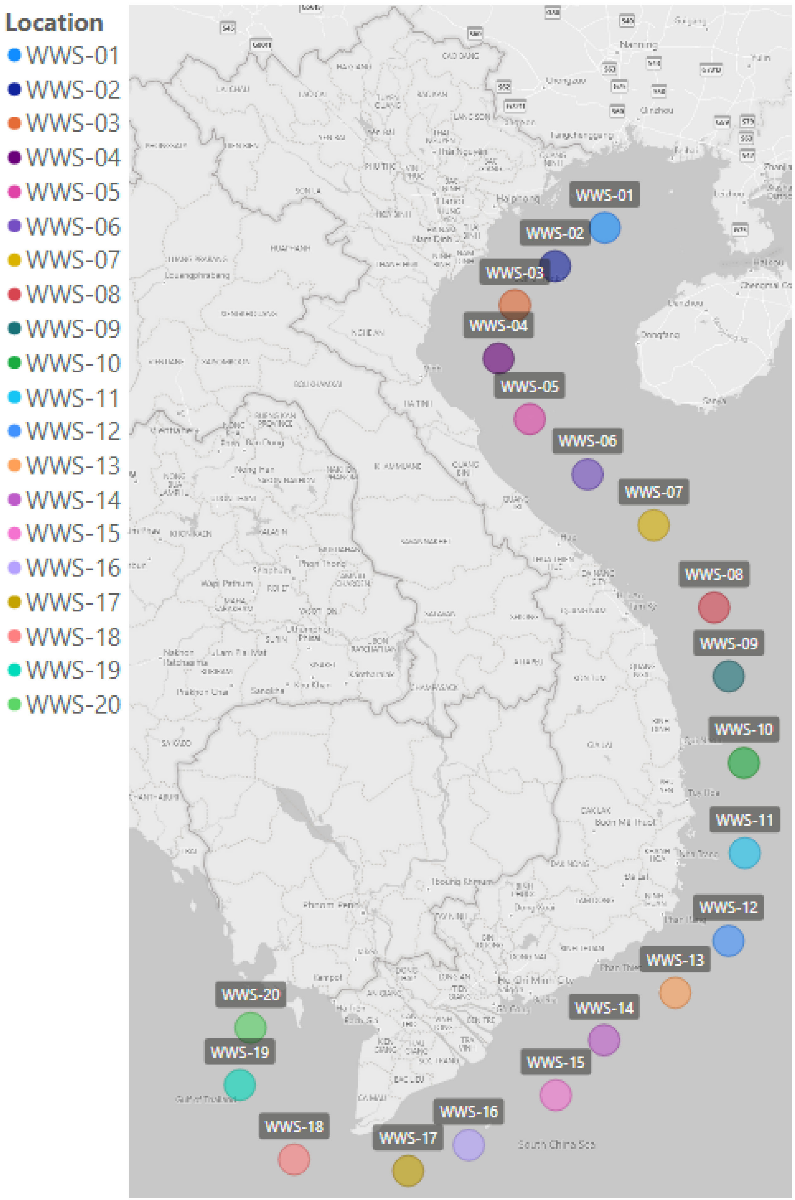


**Figure 4.** The proposed feasible locations for WWS in Vietnam.

### 4.2. Stage A: Efficiency Evaluation by B-DEA Model

To evaluate the efficiency of locations, this stage applied the B-DEA model discussed in Section 3.1. First, ten experts with at least eight years of experience in renewable energy, marine climate and public policy development were selected to contribute to this study. There are seven quantitative indicators defined by relevant research and expert opinion [17,52–54]. These indicators are divided into two groups as inputs and outputs of the B-DEA model. The inputs include bathymetry (m), distance to shore (km), and distance to the grid (km). These factors directly affect the cost of installation and maintenance and transmission power loss. Therefore, the smaller value of these metrics, the higher efficiency of WWS. Meanwhile, the population density in the adjacent residential area (people/km$^2$) as well as the energy potential related indicators of locations, such as average wind speed (m/s), annual average power density (W/m$^2$), and wave height (m), are outputs. As shown in Table 4, the data of inputs and outputs were collected from online renewable energy databases, such as the International Renewable Energy Agency database [55,56].

**Table 4.** The quantitative indicators of the B-DEA model.

| Location | Bathymetry (m) | Distance to Shore (km) | Distance to Grid (km) | Average Wind Speed (m/s) | Annual Average Power Density ($W/m^2$) | Wave Height (m) | Population Density of the Adjacent Residential Area ($People/km^2$) |
|---|---|---|---|---|---|---|---|
| WWS-1 | 40 | 77.34 | 99.44 | 7.40 | 447.14 | 0.9 | 99.62 |
| WWS-2 | 25 | 90.80 | 91.94 | 7.61 | 454.05 | 1.1 | 99.37 |
| WWS-3 | 44 | 90.20 | 118.39 | 7.61 | 454.05 | 1.1 | 87.67 |
| WWS-4 | 52 | 98.40 | 98.47 | 7.61 | 454.05 | 1.1 | 96.78 |
| WWS-5 | 69 | 73.63 | 86.49 | 7.27 | 376.72 | 1.1 | 80.88 |
| WWS-6 | 91 | 96.12 | 112.63 | 7.27 | 376.72 | 1.2 | 97.99 |
| WWS-7 | 99 | 99.02 | 99.10 | 6.85 | 318.33 | 1.4 | 94.66 |
| WWS-8 | 535 | 67.66 | 100.24 | 6.85 | 318.33 | 1.4 | 66.62 |
| WWS-9 | 439 | 90.01 | 132.21 | 7.07 | 344.87 | 1.4 | 88.70 |
| WWS-10 | 2057 | 89.88 | 96.00 | 7.07 | 344.87 | 1.4 | 90.46 |
| WWS-11 | 2152 | 85.55 | 96.82 | 6.17 | 248.00 | 1.4 | 96.19 |
| WWS-12 | 635 | 100.76 | 109.07 | 6.17 | 248.00 | 1.6 | 93.16 |
| WWS-13 | 131 | 23.70 | 98.01 | 6.17 | 248.00 | 1.5 | 91.90 |
| WWS-14 | 43 | 104.08 | 105.50 | 6.19 | 219.74 | 1.3 | 98.50 |
| WWS-15 | 40 | 98.02 | 121.95 | 6.19 | 219.74 | 1.3 | 126.72 |
| WWS-16 | 23 | 31.95 | 117.76 | 6.19 | 219.74 | 0.7 | 102.65 |
| WWS-17 | 24 | 76.49 | 129.76 | 6.19 | 219.74 | 0.8 | 78.75 |
| WWS-18 | 24 | 94.23 | 161.85 | 6.38 | 261.99 | 0.8 | 97.35 |
| WWS-19 | 42 | 78.83 | 158.20 | 6.38 | 261.99 | 0.7 | 123.08 |
| WWS-20 | 26 | 65.16 | 71.59 | 6.38 | 261.99 | 0.3 | 66.34 |

Based on the collected data, the procedure of the B-DEA model, as mentioned in Section 3.1, was applied. This study assumed that experts are more concerned with gains than losses ($\Theta > 0.5$), and $\mu = 2.25$, $\alpha = 0.85$, $\beta = 0.92$ in the B-DEA model [10]. Then, the B-DEA model (7) was solved with a different value of $\Theta$ by Lingo solver 19.0.53. The results of B-DEA's model are presented in Table A2 in Appendix A. Based on efficiency corresponding to different values of $\Theta$, locations were ranked as shown in Figure 5.

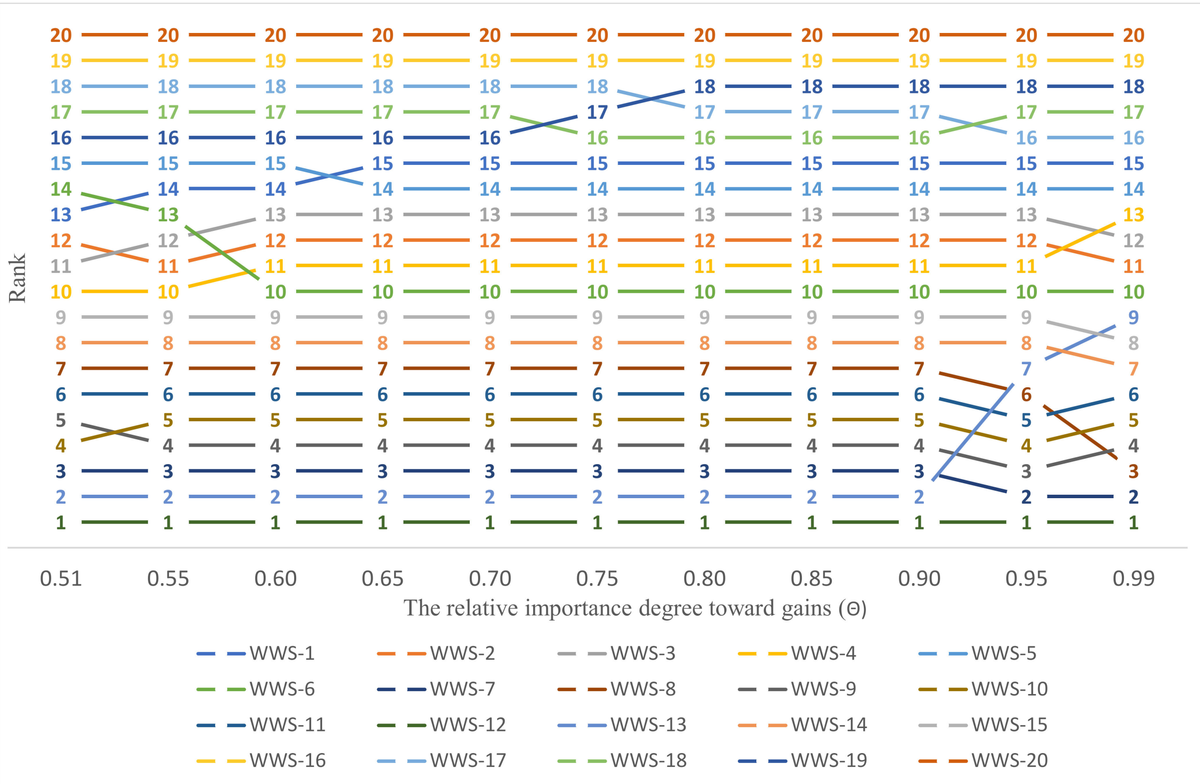


**Figure 5.** WWS location ranking with different values of Θ.

The first finding from the ranking results is that WWS-12 has the highest efficiency without being affected by Θ. Meanwhile, at the bottom of the rankings, the performance of WWS-12 and WWS-14 positions is also unchanged by the psychological behavior of the decision maker. Meanwhile, at the bottom of the rankings, the efficiency of WWS-16 and WWS-20 positions remained unchanged as decision makers place more emphasis on gains. As decision makers began to prioritize gains over losses ($0.5 < \Theta \leq 0.65$), the rankings of WWS-9, WWS-6, WWS-4, and WWS-5 improved, while WWS-10, WWS-1, and WWS-3 deteriorated. When the importance degree of gains against losses is moderate ($0.65 < \Theta \leq 0.85$), the change in rank mainly occurs at the bottom of the chart between WWS-17, WWS-18, and WWS-19. When decision makers are mostly concerned with gains ($0.85 < \Theta < 1$), the efficiency rankings are fraught with volatility. The most notable phenomenon is the severe ranking drop of WWS-13 from 2nd to 9th and the rise of WWS-8 from 7th to 3rd. In the middle of the rankings, the drop in WWS-4's ranking led to an increase in WWS-2 and WWS-3. At the bottom of the rankings, WWS-17 and WWS-18 swap positions.

### *4.3. Stage B: Sustainability Evaluation by SF DEMATEL-EDAS Method*

#### 4.3.1. Evaluation Criteria Identification and Weighting

On the other hand, this study implemented a multi-criteria evaluation of sustainability for the proposed locations. The evaluation criteria are recommended by experts and previous studies as shown in Table 5 [8,17,57–59]. Next, the experts provide linguistic pairwise comparisons of the influence between the criteria as illustrated in Table A3. Under the assumption of experts' equally weights, the aggregated SF direct influence matrix is established according to Equation (14) and presented in Table 6. As shown in Table 7, the SF total influence matrix is established by Steps 5 and 6, which were mentioned in Section 3.3.

**Table 5.** List of evaluation criteria.

| Notation | Evaluation Criteria |
|---|---|
| EC1 | Vessel density |
| EC2 | Costs |
| EC3 | Military activities |
| EC4 | Geopolitical issues |
| EC5 | Proximity to conservation area |
| EC6 | Proximity to Seaports |
| EC7 | Proximity to Industrial Area |
| EC8 | Potential tourism impact |
| EC9 | Potential fisheries impact |
| EC10 | Social acceptability |

Table A4 and Figure 6 illustrate the results of Steps 7, 8, and 9 in the SF DEMATEL–EDAS procedure mentioned above. From Figure 6, it can be seen that experts are most concerned with the costs (11.34%) and potential tourism impacts (11.04%) of WWSs. The costs such as installation, operation, maintenance, and local labor are significantly dependent on the location of the WWS. In addition, the potential effects of WWS on the tourism industry are of great concern to experts because it contributes more than six percent to Vietnam's economy [60]. The social acceptability (10.29%), proximity to industrial area (10.70%), and vessel density (10.93%) are approximately equally weighted groups of criteria. The next lower weighted group includes potential fisheries impact (9.73%), proximity to seaports (9.48%), vessel density (9.51%), and military activities (9.51%). Although the western Pacific region has many sovereignty issues, experts consider geopolitical factor (7.03%) with the lowest weight to assess the sustainability of WWSs.

**Table 6.** Aggregated spherical fuzzy direct influence matrix.

| Criteria | EC1 | EC2 | EC3 | EC4 | EC5 |
|---|---|---|---|---|---|
| EC1 | (0.00, 0.30, 0.20) | (0.73, 0.19, 0.49) | (0.62, 0.22, 0.48) | (0.65, 0.21, 0.47) | (0.59, 0.22, 0.44) |
| EC2 | (0.66, 0.21, 0.49) | (0.00, 0.30, 0.20) | (0.52, 0.23, 0.39) | (0.59, 0.22, 0.44) | (0.61, 0.22, 0.48) |
| EC3 | (0.54, 0.24, 0.44) | (0.70, 0.19, 0.48) | (0.00, 0.30, 0.20) | (0.57, 0.23, 0.44) | (0.67, 0.21, 0.49) |
| EC4 | (0.38, 0.25, 0.27) | (0.49, 0.24, 0.38) | (0.36, 0.26, 0.27) | (0.00, 0.30, 0.20) | (0.52, 0.23, 0.39) |
| EC5 | (0.66, 0.21, 0.49) | (0.69, 0.20, 0.49) | (0.57, 0.23, 0.44) | (0.64, 0.21, 0.47) | (0.00, 0.30, 0.20) |
| EC6 | (0.30, 0.27, 0.25) | (0.65, 0.20, 0.47) | (0.57, 0.22, 0.44) | (0.68, 0.20, 0.49) | (0.62, 0.21, 0.44) |
| EC7 | (0.72, 0.19, 0.49) | (0.65, 0.20, 0.47) | (0.69, 0.20, 0.49) | (0.63, 0.22, 0.47) | (0.46, 0.25, 0.38) |
| EC8 | (0.77, 0.17, 0.48) | (0.57, 0.22, 0.44) | (0.64, 0.21, 0.47) | (0.70, 0.19, 0.48) | (0.71, 0.20, 0.50) |
| EC9 | (0.59, 0.22, 0.44) | (0.70, 0.20, 0.50) | (0.59, 0.21, 0.40) | (0.55, 0.23, 0.44) | (0.58, 0.22, 0.44) |
| EC10 | (0.64, 0.21, 0.47) | (0.56, 0.22, 0.40) | (0.72, 0.19, 0.49) | (0.53, 0.23, 0.39) | (0.59, 0.22, 0.44) |
| **Criteria** | **EC6** | **EC7** | **EC8** | **EC9** | **EC10** |
| EC1 | (0.70, 0.19, 0.48) | (0.65, 0.2, 0.44) | (0.61, 0.21, 0.44) | (0.63, 0.21, 0.44) | (0.49, 0.24, 0.38) |
| EC2 | (0.65, 0.21, 0.47) | (0.57, 0.22, 0.44) | (0.46, 0.25, 0.38) | (0.69, 0.20, 0.49) | (0.69, 0.20, 0.48) |
| EC3 | (0.60, 0.21, 0.44) | (0.60, 0.21, 0.44) | (0.45, 0.25, 0.38) | (0.46, 0.25, 0.38) | (0.45, 0.25, 0.38) |
| EC4 | (0.35, 0.26, 0.27) | (0.38, 0.25, 0.27) | (0.38, 0.26, 0.28) | (0.27, 0.27, 0.23) | (0.44, 0.24, 0.30) |
| EC5 | (0.48, 0.23, 0.31) | (0.40, 0.25, 0.29) | (0.61, 0.21, 0.44) | (0.57, 0.22, 0.44) | (0.52, 0.23, 0.39) |
| EC6 | (0.00, 0.30, 0.20) | (0.65, 0.22, 0.50) | (0.64, 0.22, 0.50) | (0.59, 0.23, 0.48) | (0.53, 0.23, 0.39) |
| EC7 | (0.63, 0.22, 0.47) | (0.00, 0.30, 0.20) | (0.46, 0.25, 0.38) | (0.60, 0.22, 0.44) | (0.69, 0.20, 0.48) |
| EC8 | (0.67, 0.20, 0.49) | (0.78, 0.18, 0.49) | (0.00, 0.30, 0.20) | (0.69, 0.20, 0.48) | (0.77, 0.17, 0.48) |
| EC9 | (0.36, 0.26, 0.27) | (0.68, 0.20, 0.49) | (0.64, 0.21, 0.47) | (0.00, 0.30, 0.20) | (0.65, 0.20, 0.47) |
| EC10 | (0.61, 0.21, 0.44) | (0.62, 0.21, 0.44) | (0.61, 0.22, 0.48) | (0.48, 0.23, 0.31) | (0.00, 0.30, 0.20) |

**Table 7.** Spherical fuzzy total influence matrix.

| Criteria | EC1 | EC2 | EC3 | EC4 | EC5 |
|---|---|---|---|---|---|
| EC1 | (0.45, 0.79, 0.87) | (0.59, 0.71, 0.98) | (0.54, 0.76, 0.93) | (0.56, 0.74, 0.98) | (0.54, 0.75, 0.95) |
| EC2 | (0.53, 0.77, 0.93) | (0.47, 0.78, 0.93) | (0.51, 0.79, 0.92) | (0.54, 0.77, 0.97) | (0.52, 0.78, 0.96) |
| EC3 | (0.48, 0.81, 0.89) | (0.53, 0.76, 0.95) | (0.40, 0.84, 0.84) | (0.50, 0.80, 0.94) | (0.50, 0.80, 0.93) |
| EC4 | (0.35, 0.89, 0.63) | (0.39, 0.85, 0.68) | (0.35, 0.89, 0.63) | (0.30, 0.89, 0.64) | (0.37, 0.88, 0.67) |
| EC5 | (0.50, 0.79, 0.88) | (0.54, 0.76, 0.92) | (0.49, 0.80, 0.87) | (0.52, 0.78, 0.92) | (0.41, 0.83, 0.84) |
| EC6 | (0.46, 0.81, 0.86) | (0.54, 0.76, 0.96) | (0.50, 0.80, 0.91) | (0.53, 0.77, 0.96) | (0.51, 0.79, 0.93) |
| EC7 | (0.54, 0.76, 0.93) | (0.57, 0.73, 0.98) | (0.53, 0.76, 0.94) | (0.55, 0.76, 0.98) | (0.51, 0.78, 0.94) |
| EC8 | (0.60, 0.69, 0.98) | (0.62, 0.69, 0.99) | (0.59, 0.71, 0.98) | (0.62, 0.69, 0.99) | (0.60, 0.70, 0.99) |
| EC9 | (0.51, 0.78, 0.90) | (0.56, 0.74, 0.96) | (0.51, 0.78, 0.89) | (0.53, 0.77, 0.95) | (0.52, 0.78, 0.93) |
| EC10 | (0.52, 0.77, 0.90) | (0.54, 0.75, 0.93) | (0.53, 0.77, 0.90) | (0.52, 0.77, 0.93) | (0.52, 0.78, 0.92) |
| **Criteria** | **EC6** | **EC7** | **EC8** | **EC9** | **EC10** |
| EC1 | (0.53, 0.75, 0.89) | (0.54, 0.74, 0.91) | (0.50, 0.78, 0.90) | (0.52, 0.77, 0.89) | (0.52, 0.76, 0.89) |
| EC2 | (0.51, 0.78, 0.89) | (0.52, 0.77, 0.91) | (0.47, 0.82, 0.89) | (0.51, 0.79, 0.90) | (0.53, 0.77, 0.91) |
| EC3 | (0.47, 0.81, 0.85) | (0.49, 0.08, 0.88) | (0.44, 0.85, 0.86) | (0.45, 0.84, 0.85) | (0.46, 0.82, 0.86) |
| EC4 | (0.33, 0.90, 0.60) | (0.35, 0.88, 0.62) | (0.33, 0.93, 0.61) | (0.32, 0.91, 0.60) | (0.35, 0.88, 0.62) |
| EC5 | (0.46, 0.81, 0.80) | (0.47, 0.80, 0.82) | (0.47, 0.83, 0.85) | (0.47, 0.81, 0.84) | (0.48, 0.80, 0.84) |
| EC6 | (0.40, 0.84, 0.81) | (0.51, 0.79, 0.90) | (0.47, 0.83, 0.89) | (0.48, 0.82, 0.88) | (0.49, 0.80, 0.88) |
| EC7 | (0.51, 0.78, 0.89) | (0.44, 0.80, 0.86) | (0.47, 0.81, 0.89) | (0.50, 0.79, 0.90) | (0.53, 0.76, 0.92) |
| EC8 | (0.57, 0.71, 0.94) | (0.61, 0.69, 0.97) | (0.46, 0.77, 0.90) | (0.57, 0.72, 0.95) | (0.60, 0.69, 0.96) |
| EC9 | (0.46, 0.81, 0.83) | (0.53, 0.77, 0.90) | (0.49, 0.81, 0.88) | (0.41, 0.83, 0.82) | (0.52, 0.77, 0.89) |
| EC10 | (0.50, 0.79, 0.85) | (0.52, 0.77, 0.88) | (0.48, 0.81, 0.88) | (0.48, 0.80, 0.84) | (0.42, 0.81, 0.82) |

#### 4.3.2. Sustainability Ranking

After determining the weights of the evaluation criteria, the next calculations are to evaluate and rank the locations according to the criteria. First, individual linguistic assessments were provided by each expert as illustrated in Table A3. In the expert survey, the higher linguistic terms, the better the potential of locations for the criteria. In other words, the evaluation criteria are considered as benefit criteria. Then, the individual spherical fuzzy decision matrices are formed by the SFN transformation according to

Table 3. By using SWAM, individual spherical fuzzy decision matrices are synthesized to form a spherical fuzzy decision matrix as shown in Table A6. Based on the spherical fuzzy decision matrix, the average spherical fuzzy solution was determined according to Equation (34) and as shown in Table A7. The defuzzification process for the spherical fuzzy decision matrix and the spherical fuzzy averaging solution was performed and is illustrated as shown in Table A8. Tables A9 and A10 present the positive distances from the average solution and the negative distance from the average solution as Equations (37) and (38). Continuing to perform the calculations according to Step 13 and Step 14 as mentioned in Section 3.3, the results of assessing the sustainability of the locations are presented in Table 8. According to the ranking results, WWS-11, WWS-13, and WWS-7 ranked first three in terms of sustainability. In contrast, at the bottom of the sustainability rankings are WWS-17, WWS-16, and WWS-10, respectively.

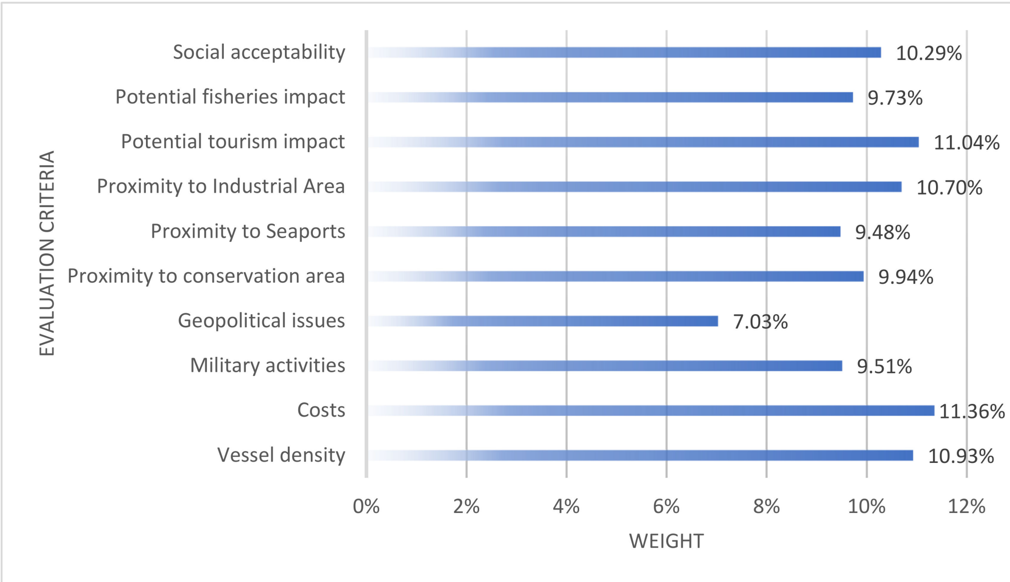


**Figure 6.** Evaluation criteria weight.

**Table 8.** Spherical fuzzy EDAS results.

| Location | $s_i^+$ | $s_i^-$ | $ns_i^+$ | $ns_i^-$ | $as_i$ | Location | $s_i^+$ | $s_i^-$ | $ns_i^+$ | $ns_i^-$ | $as_i$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| WWS-1 | 0.288 | 0.120 | 0.593 | 0.62 | 0.606 | WWS-11 | 0.472 | 0.035 | 0.97 | 0.889 | 0.930 |
| WWS-2 | 0.243 | 0.168 | 0.499 | 0.466 | 0.482 | WWS-12 | 0.353 | 0.080 | 0.726 | 0.746 | 0.736 |
| WWS-3 | 0.147 | 0.043 | 0.303 | 0.863 | 0.583 | WWS-13 | 0.442 | 0.105 | 0.907 | 0.668 | 0.788 |
| WWS-4 | 0.143 | 0.190 | 0.295 | 0.398 | 0.346 | WWS-14 | 0.325 | 0.220 | 0.668 | 0.301 | 0.485 |
| WWS-5 | 0.191 | 0.057 | 0.392 | 0.82 | 0.606 | WWS-15 | 0.385 | 0.160 | 0.792 | 0.492 | 0.642 |
| WWS-6 | 0.107 | 0.174 | 0.221 | 0.449 | 0.335 | WWS-16 | 0.102 | 0.302 | 0.21 | 0.042 | 0.126 |
| WWS-7 | 0.487 | 0.166 | 1 | 0.473 | 0.736 | WWS-17 | 0.194 | 0.277 | 0.399 | 0.122 | 0.260 |
| WWS-8 | 0.140 | 0.055 | 0.288 | 0.827 | 0.557 | WWS-18 | 0.350 | 0.173 | 0.719 | 0.452 | 0.585 |
| WWS-9 | 0.397 | 0.122 | 0.815 | 0.612 | 0.713 | WWS-19 | 0.109 | 0.139 | 0.224 | 0.559 | 0.392 |
| WWS-10 | 0.112 | 0.315 | 0.231 | 0 | 0.116 | WWS-20 | 0.197 | 0.130 | 0.405 | 0.589 | 0.497 |

*4.4. Dual-Side Analysis*

To evaluate the potential of locations in terms of both efficiency and sustainability, the quantitative results of the B-DEA model and the qualitative results of the SF DEMATEL–EDAS approach were compiled as shown in Table A11. Considering the two factors of sustainability and efficiency, Figure 7 below illustrates the positioning maps for the potential of locations under different decision makers' psychological behavior. From Figure 7, the positioning maps are divided into four quadrants. The lower left quadrant implies locations that rank high in both sustainability and efficiency. The lower right quadrant includes locations with high sustainability but low efficiency. In contrast, locations in the upper left quadrant have high efficiency but low sustainability. Finally, the upper right quadrant includes locations that rank low in both sustainability and efficiency. As the psychological behavior of decision makers changes in favor of gains versus losses, locations' positions of on the positioning map change. However, recognized position changes do not extend beyond its original quadrant. The exception is the position change of WWS-4 and WWS-6. As the importance degree towards gains increases, WWS-4 moves into quadrant IV. Meanwhile, WWS-6 tends to move towards the origin of quadrant III. Based on the positioning maps, this study classifies the potential of locations into four groups of recommended, sustainable, efficient, and considered as shown in Table 9.

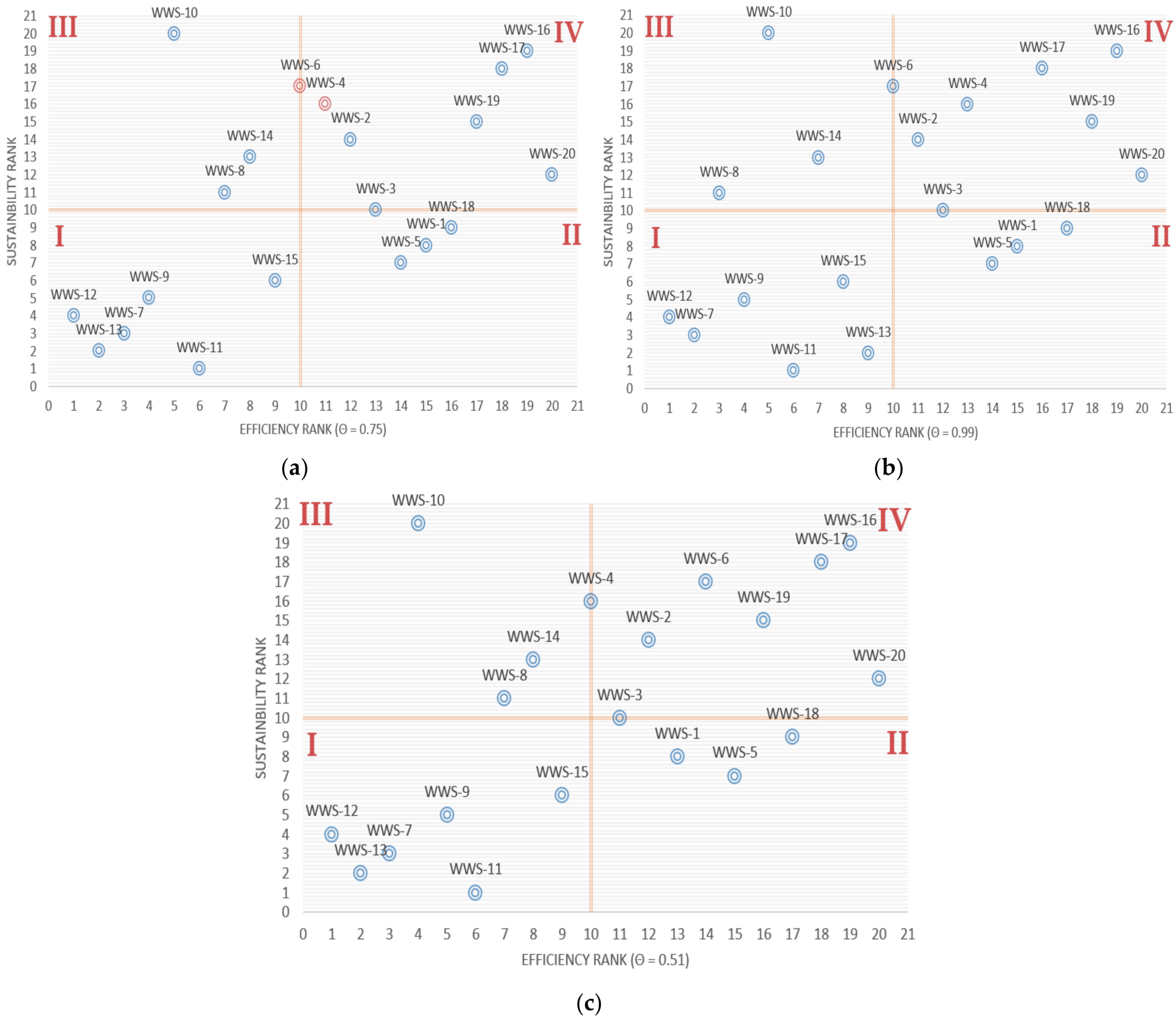


**Figure 7.** Positioning maps of WWS locations: (**a**) Under moderate importance degree toward gains; (**b**) Under high importance degree toward gains; (**c**) Under low importance degree toward gains.

**Table 9.** Location classification for WWS.

| Group | Locations |
|---|---|
| Recommended locations | WWS-7, WWS-9, WWS-11, WWS-12, WWS-13, WWS-15 |
| Sustainable locations | WWS-1, WWS-3, WWS-5, WWS-18 |
| Efficient locations | WWS-6, WWS-8, WWS-10, WWS-14 |
| Considered locations | WWS-2, WWS-4, WWS-16, WWS-17, WWS-19 |

### 4.5. Managerial Implications

According to statistics, the current offshore wind energy projects of Vietnam are mainly concentrated in the Southeast region as illustrated in Figure 8 [61]. As illustrated in Figure 9, the recommended locations for the installation of WWSs are distributed from Quang Tri province in the central region to Soc Trang province in the Mekong Delta. Meanwhile, the marine coordinates in the north of Vietnam mainly belong to the group of locations with high sustainability. Thus, the suggestions on both efficient and sustainable locations in this study are useful references for managers and investors to design and develop integrated wind and wave energy projects in the future.

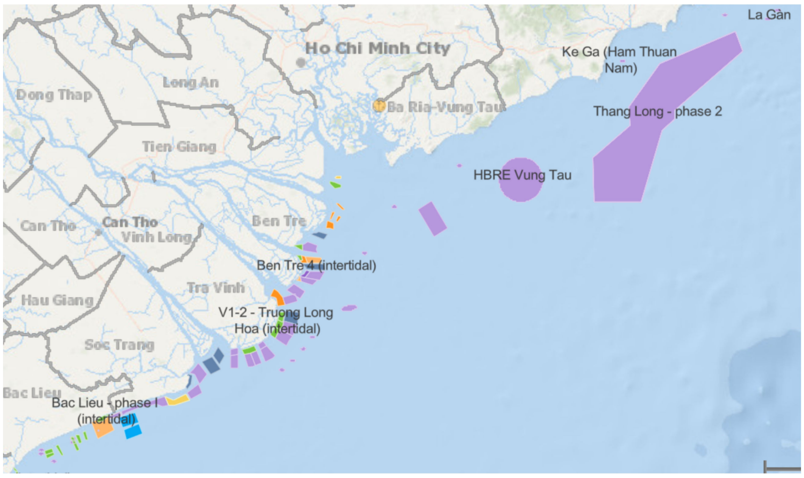


**Figure 8.** Vietnam offshore wind energy project locations (Source: 4C Offshore Ltd.).

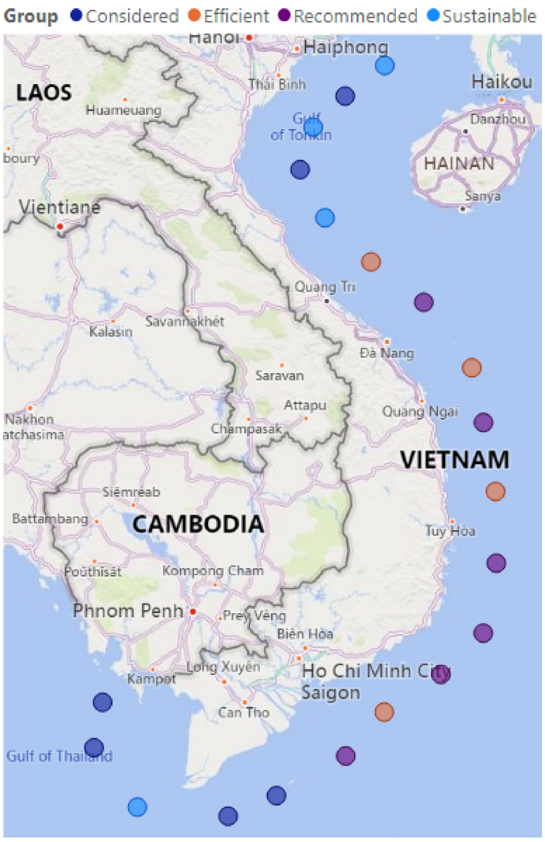


**Figure 9.** Recommended locations for WWS in Vietnam.

The proposed dual-site approach allows for independent evaluation of both efficiency and sustainability of locations. Moreover, this approach both ensures the objectivity of the data and synthesizes subjective expert opinions in the evaluation process. This novel behavioral approach could be applied to decision-making problems in other areas that are influenced by human nature.

## 5. Conclusions

### 5.1. Contributions and Findings

Harnessing the potential of energy from the ocean in terms of both wind and waves through integrated offshore renewable energy stations is a promising solution for the sustainable development of many countries. With the continuous evolution of integrated energy conversion technology, the necessity of choosing both sustainable and efficient locations for WWSs is great. Vietnam's offshore wind energy development roadmap has been studied in recent years. However, wind and wave integrated stations have not been sufficiently analyzed and evaluated. Therefore, this study proposed a novel dual-side behavioral spherical fuzzy multi-criteria decision-making approach to accomplish that purpose.

As for the practical contribution, a comprehensive assessment of the sustainability and efficiency of locations along the coast of Vietnam was provided. Accordingly, locations are classified into recommended, sustainable, efficient, and considered groups. Renewable energy investors and developers can refer to this classification in their future decisions. As for the theoretical contribution, this study proposed a dual-side approach, which has novelties on each side. To perform the quantitative evaluation, a BDEA model, which is extended according to prospect theory, was used to evaluate the efficiency of alternatives under the consideration of the decision makers' psychological behavior. In parallel, an MCDM method combining the SF DEMATEL and SF EDAS methods was used for the multi-criteria qualitative evaluation. Then, the qualitative and quantitative evaluation results were aggregated to provide the overall evaluation results.

The practical findings of this study indicate that the recommended locations, whose efficiency and sustainability are high, for the installation of WWSs are distributed from Quang Tri province in the central region to Soc Trang province in the Mekong Delta. Meanwhile, the marine coordinates in the north of Vietnam mainly belong to the group of locations with high sustainability.

### 5.2. Limitations and Futher Research Recommendations

The main limitation of this study is that it has not fully explored other behavioral parameters, such as loss aversion $(\mu)$ and attitudes towards gains $(\alpha)$ and losses $(\beta)$ in the B-DEA model. The lack of more complex sensitivity analyzes of the weights of the evaluation criteria are another limitation of this study. Therefore, further studies are suggested to perform complex sensitivity analyzes for behavioral parameters. Moreover, further assessments of wave climates could enhance the ranking results of this study.

**Author Contributions:** Conceptualization, M.-T.L. and N.-L.N.; methodology, N.-L.N.; validation, M.-T.L. and N.-L.N.; formal analysis, M.-T.L. and N.-L.N.; investigation, M.-T.L. and N.-L.N.; data curation, M.-T.L. and N.-L.N.; writing—original draft preparation, N.-L.N.; writing—review and editing, M.-T.L. and N.-L.N.; project administration, N.-L.N.; funding acquisition, M.-T.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work belongs to the 2022 project funded by Ho Chi Minh City University of Technology and Education, Vietnam.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors appreciate the support from the Ho Chi Minh City University of Technology and Education, Vietnam. The authors sincerely thank the valuable technical comments from the reviewers.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** The proposed locations' coordinates.

| Location | Latitude | Longitude | Location | Latitude | Longitude |
|---|---|---|---|---|---|
| WWS-1 | 20.591686 | 108.202101 | WWS-11 | 12.380291 | 110.120526 |
| WWS-2 | 20.097773 | 107.519992 | WWS-12 | 11.200562 | 109.896527 |
| WWS-3 | 19.594143 | 106.968776 | WWS-13 | 10.503389 | 109.167185 |
| WWS-4 | 18.903735 | 106.745225 | WWS-14 | 9.862731 | 108.192441 |
| WWS-5 | 18.116894 | 107.173398 | WWS-15 | 9.118867 | 107.530793 |
| WWS-6 | 17.393742 | 107.965662 | WWS-16 | 8.443364 | 106.337667 |
| WWS-7 | 16.727761 | 108.872040 | WWS-17 | 8.092894 | 105.506814 |
| WWS-8 | 15.643628 | 109.700175 | WWS-18 | 8.247452 | 103.944320 |
| WWS-9 | 14.734740 | 109.899698 | WWS-19 | 9.257728 | 103.199160 |
| WWS-10 | 13.583723 | 110.107265 | WWS-20 | 10.029545 | 103.346960 |

**Table A2.** The results of the B-DEA model.

| Location | Value of Θ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **0.51** | **0.55** | **0.60** | **0.65** | **0.70** | **0.75** | **0.80** | **0.85** | **0.90** | **0.95** | **0.99** |
| WWS-1 | 0.027 | 0.071 | 0.126 | 0.182 | 0.237 | 0.293 | 0.394 | 0.495 | 0.596 | 0.696 | 0.797 |
| WWS-2 | 0.046 | 0.089 | 0.143 | 0.201 | 0.288 | 0.375 | 0.462 | 0.549 | 0.636 | 0.723 | 0.810 |
| WWS-3 | 0.046 | 0.089 | 0.143 | 0.201 | 0.288 | 0.375 | 0.462 | 0.549 | 0.636 | 0.723 | 0.810 |
| WWS-4 | 0.047 | 0.090 | 0.144 | 0.202 | 0.289 | 0.376 | 0.463 | 0.550 | 0.637 | 0.724 | 0.810 |
| WWS-5 | 0.016 | 0.061 | 0.117 | 0.198 | 0.286 | 0.373 | 0.461 | 0.548 | 0.635 | 0.723 | 0.810 |
| WWS-6 | 0.021 | 0.079 | 0.161 | 0.242 | 0.324 | 0.406 | 0.488 | 0.569 | 0.651 | 0.733 | 0.814 |
| WWS-7 | 0.102 | 0.160 | 0.234 | 0.307 | 0.380 | 0.453 | 0.526 | 0.600 | 0.673 | 0.746 | 0.819 |
| WWS-8 | 0.096 | 0.155 | 0.228 | 0.301 | 0.375 | 0.449 | 0.523 | 0.597 | 0.671 | 0.745 | 0.819 |
| WWS-9 | 0.100 | 0.159 | 0.232 | 0.306 | 0.379 | 0.452 | 0.526 | 0.599 | 0.673 | 0.746 | 0.819 |
| WWS-10 | 0.100 | 0.159 | 0.232 | 0.306 | 0.379 | 0.452 | 0.526 | 0.599 | 0.673 | 0.746 | 0.819 |
| WWS-11 | 0.099 | 0.158 | 0.231 | 0.305 | 0.378 | 0.452 | 0.525 | 0.599 | 0.672 | 0.746 | 0.819 |
| WWS-12 | 0.174 | 0.227 | 0.293 | 0.359 | 0.425 | 0.491 | 0.557 | 0.624 | 0.690 | 0.756 | 0.822 |
| WWS-13 | 0.128 | 0.184 | 0.254 | 0.324 | 0.394 | 0.464 | 0.534 | 0.605 | 0.675 | 0.745 | 0.815 |
| WWS-14 | 0.062 | 0.123 | 0.201 | 0.278 | 0.355 | 0.432 | 0.509 | 0.586 | 0.663 | 0.740 | 0.817 |
| WWS-15 | 0.061 | 0.122 | 0.200 | 0.277 | 0.354 | 0.431 | 0.508 | 0.586 | 0.663 | 0.740 | 0.817 |
| WWS-16 | 0.008 | 0.048 | 0.099 | 0.150 | 0.201 | 0.252 | 0.303 | 0.404 | 0.525 | 0.646 | 0.767 |
| WWS-17 | 0.009 | 0.050 | 0.101 | 0.152 | 0.203 | 0.254 | 0.347 | 0.457 | 0.567 | 0.677 | 0.787 |
| WWS-18 | 0.013 | 0.054 | 0.104 | 0.155 | 0.206 | 0.257 | 0.349 | 0.458 | 0.568 | 0.677 | 0.787 |
| WWS-19 | 0.014 | 0.055 | 0.105 | 0.156 | 0.207 | 0.257 | 0.308 | 0.407 | 0.529 | 0.650 | 0.771 |
| WWS-20 | 0.006 | 0.047 | 0.098 | 0.149 | 0.201 | 0.252 | 0.303 | 0.355 | 0.406 | 0.464 | 0.524 |

**Table A3.** Linguistic pairwise comparison of criteria by Expert 1.

| Criteria | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| EC1 | NI | WI | NI | SI | WI | WI | WI | SI | MI | NI |
| EC2 | SI | NI | MI | NI | SI | SI | WI | NI | MI | SI |
| EC3 | NI | MI | NI | WI | NI | WI | WI | WI | SI | WI |
| EC4 | WI | NI | NI | NI | NI | WI | WI | MI | NI | WI |
| EC5 | SI | SI | NI | SI | NI | MI | MI | MI | SI | SI |
| EC6 | WI | MI | MI | SI | WI | NI | SI | SI | WI | MI |
| EC7 | MI | WI | SI | SI | MI | WI | NI | WI | MI | SI |
| EC8 | SI | MI | NI | MI | WI | WI | SI | NI | NI | SI |
| EC9 | NI | SI | MI | WI | SI | NI | SI | NI | NI | SI |
| EC10 | MI | WI | MI | SI | MI | SI | MI | MI | WI | NI |

**Table A4.** Spherical fuzzy DEMATEL results.

| Criteria | $\tilde{R}$ | R | $\tilde{C}$ | C | Prominence | Relation | Weight |
|---|---|---|---|---|---|---|---|
| EC1 | (0.981, 0.060, 0.193) | 0.639 | (0.972, 0.090, 0.236) | 0.562 | 1.201 | 0.077 | 0.109 |
| EC2 | (0.975, 0.086, 0.223) | 0.584 | (0.984, 0.058, 0.178) | 0.664 | 1.248 | −0.080 | 0.114 |
| EC3 | (0.960, 0.126, 0.281) | 0.484 | (0.972, 0.093, 0.237) | 0.561 | 1.045 | −0.077 | 0.095 |
| EC4 | (0.847, 0.311, 0.530) | 0.148 | (0.980, 0.074, 0.200) | 0.624 | 0.773 | −0.476 | 0.070 |
| EC5 | (0.964, 0.106, 0.264) | 0.516 | (0.974, 0.090, 0.227) | 0.577 | 1.092 | −0.061 | 0.099 |
| EC6 | (0.968, 0.107, 0.252) | 0.534 | (0.963, 0.104, 0.270) | 0.508 | 1.042 | 0.026 | 0.095 |
| EC7 | (0.977, 0.076, 0.212) | 0.605 | (0.973, 0.080, 0.232) | 0.571 | 1.176 | 0.034 | 0.107 |
| EC8 | (0.993, 0.031, 0.122) | 0.767 | (0.953, 0.145, 0.303) | 0.447 | 1.214 | 0.319 | 0.110 |
| EC9 | (0.974, 0.087, 0.228) | 0.576 | (0.961, 0.116, 0.277) | 0.493 | 1.069 | 0.082 | 0.097 |
| EC10 | (0.973, 0.083, 0.229) | 0.576 | (0.970, 0.086, 0.242) | 0.555 | 1.131 | 0.021 | 0.103 |

**Table A5.** Linguistic evaluation by Expert 1.

| Location | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| WWS-1 | M | L | M | SH | VH | H | SH | M | L | VHI |
| WWS-2 | H | L | L | SH | AL | H | L | M | SH | AL |
| WWS-3 | AH | VH | VL | H | AL | M | VL | VL | H | AH |
| WWS-4 | VH | VH | SH | L | VL | AL | VH | H | H | H |
| WWS-5 | SH | SH | L | M | VL | SH | AH | SL | VH | AH |
| WWS-6 | SH | SH | AH | VL | H | SH | SH | AH | H | SH |
| WWS-7 | AH | VL | H | VH | SL | VL | M | VH | AH | SL |
| WWS-8 | VL | VL | VL | AH | M | AH | AL | SL | VH | H |
| WWS-9 | AL | AH | L | H | H | SH | SL | SL | H | VH |
| WWS-10 | AL | SH | AH | VH | VH | M | H | M | VL | M |
| WWS-11 | SH | VL | VL | L | VH | L | AH | VH | VH | SL |
| WWS-12 | H | SH | L | H | L | AL | VH | SH | VL | VL |
| WWS-13 | VH | H | AH | VH | M | SL | VH | VL | M | SL |
| WWS-14 | VH | VH | AL | SL | SL | M | AH | AL | SL | M |
| WWS-15 | AH | AL | M | AH | VH | SL | SL | VL | AH | L |
| WWS-16 | SH | AL | VH | VH | VL | SL | L | SL | VL | H |
| WWS-17 | L | M | VL | VL | SL | AH | SH | H | AL | VH |
| WWS-18 | SL | AH | VH | AH | SL | VL | VL | AL | M | L |
| WWS-19 | SL | AL | L | L | L | AL | VL | VL | H | AL |
| WWS-20 | SH | AH | H | VL | AH | SL | M | SL | VL | AL |

**Table A6.** Spherical fuzzy decision matrix.

| Location | EC1 | EC2 | EC3 | EC4 | EC5 |
|---|---|---|---|---|---|
| WWS-1 | (0.73, 0.28, 0.31) | (0.66, 0.37, 0.29) | (0.70, 0.33, 0.33) | (0.62, 0.41, 0.33) | (0.66, 0.35, 0.31) |
| WWS-2 | (0.58, 0.46, 0.30) | (0.56, 0.46, 0.36) | (0.40, 0.64, 0.31) | (0.57, 0.47, 0.35) | (0.57, 0.48, 0.32) |
| WWS-3 | (0.66, 0.37, 0.29) | (0.68, 0.33, 0.31) | (0.50, 0.56, 0.34) | (0.74, 0.27, 0.30) | (0.66, 0.38, 0.27) |
| WWS-4 | (0.61, 0.42, 0.30) | (0.69, 0.33, 0.25) | (0.61, 0.44, 0.25) | (0.68, 0.35, 0.27) | (0.56, 0.49, 0.31) |
| WWS-5 | (0.63, 0.42, 0.27) | (0.62, 0.41, 0.31) | (0.67, 0.37, 0.27) | (0.72, 0.29, 0.28) | (0.60, 0.45, 0.26) |
| WWS-6 | (0.57, 0.46, 0.31) | (0.63, 0.39, 0.31) | (0.70, 0.33, 0.29) | (0.70, 0.35, 0.24) | (0.68, 0.35, 0.28) |
| WWS-7 | (0.79, 0.22, 0.24) | (0.52, 0.53, 0.33) | (0.66, 0.37, 0.28) | (0.66, 0.36, 0.30) | (0.62, 0.40, 0.34) |
| WWS-8 | (0.63, 0.40, 0.31) | (0.61, 0.43, 0.31) | (0.57, 0.48, 0.29) | (0.68, 0.36, 0.26) | (0.55, 0.51, 0.30) |
| WWS-9 | (0.54, 0.49, 0.37) | (0.67, 0.37, 0.24) | (0.64, 0.39, 0.31) | (0.65, 0.39, 0.27) | (0.65, 0.38, 0.31) |
| WWS-10 | (0.51, 0.53, 0.31) | (0.49, 0.54, 0.34) | (0.59, 0.44, 0.36) | (0.49, 0.56, 0.31) | (0.71, 0.33, 0.24) |
| WWS-11 | (0.77, 0.25, 0.21) | (0.55, 0.50, 0.31) | (0.64, 0.39, 0.30) | (0.65, 0.38, 0.29) | (0.64, 0.40, 0.28) |
| WWS-12 | (0.67, 0.35, 0.32) | (0.62, 0.41, 0.32) | (0.64, 0.39, 0.28) | (0.70, 0.32, 0.24) | (0.69, 0.35, 0.23) |
| WWS-13 | (0.70, 0.32, 0.31) | (0.71, 0.33, 0.20) | (0.64, 0.38, 0.29) | (0.67, 0.37, 0.26) | (0.48, 0.53, 0.40) |
| WWS-14 | (0.66, 0.36, 0.29) | (0.70, 0.32, 0.28) | (0.60, 0.44, 0.28) | (0.63, 0.40, 0.28) | (0.61, 0.42, 0.35) |
| WWS-15 | (0.76, 0.26, 0.20) | (0.51, 0.53, 0.29) | (0.68, 0.35, 0.28) | (0.72, 0.31, 0.24) | (0.57, 0.47, 0.35) |
| WWS-16 | (0.69, 0.33, 0.28) | (0.59, 0.44, 0.39) | (0.69, 0.34, 0.28) | (0.73, 0.30, 0.22) | (0.58, 0.45, 0.34) |
| WWS-17 | (0.60, 0.44, 0.30) | (0.60, 0.44, 0.32) | (0.66, 0.40, 0.22) | (0.60, 0.45, 0.28) | (0.46, 0.57, 0.37) |
| WWS-18 | (0.55, 0.47, 0.37) | (0.56, 0.49, 0.28) | (0.68, 0.35, 0.31) | (0.67, 0.36, 0.30) | (0.79, 0.22, 0.20) |
| WWS-19 | (0.55, 0.48, 0.34) | (0.58, 0.46, 0.31) | (0.42, 0.60, 0.34) | (0.78, 0.23, 0.21) | (0.58, 0.47, 0.28) |
| WWS-20 | (0.67, 0.35, 0.31) | (0.63, 0.39, 0.35) | (0.74, 0.29, 0.20) | (0.63, 0.4, 0.28) | (0.66, 0.38, 0.28) |

**Table A6.** *Cont.*

| Location | EC6 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|
| WWS-1 | (0.64, 0.38, 0.30) | (0.65, 0.38, 0.31) | (0.51, 0.54, 0.32) | (0.53, 0.48, 0.39) | (0.75, 0.27, 0.20) |
| WWS-2 | (0.67, 0.34, 0.35) | (0.69, 0.33, 0.28) | (0.64, 0.39, 0.28) | (0.64, 0.39, 0.32) | (0.70, 0.35, 0.20) |
| WWS-3 | (0.59, 0.46, 0.30) | (0.62, 0.43, 0.30) | (0.63, 0.39, 0.32) | (0.60, 0.45, 0.26) | (0.53, 0.53, 0.29) |
| WWS-4 | (0.50, 0.56, 0.29) | (0.57, 0.45, 0.36) | (0.63, 0.40, 0.30) | (0.52, 0.51, 0.38) | (0.59, 0.45, 0.33) |
| WWS-5 | (0.66, 0.35, 0.33) | (0.62, 0.44, 0.22) | (0.49, 0.55, 0.33) | (0.51, 0.53, 0.32) | (0.65, 0.39, 0.29) |
| WWS-6 | (0.68, 0.35, 0.32) | (0.47, 0.55, 0.37) | (0.60, 0.43, 0.34) | (0.57, 0.47, 0.28) | (0.57, 0.46, 0.35) |
| WWS-7 | (0.60, 0.45, 0.27) | (0.59, 0.45, 0.32) | (0.79, 0.22, 0.18) | (0.66, 0.36, 0.32) | (0.51, 0.50, 0.36) |
| WWS-8 | (0.61, 0.44, 0.25) | (0.64, 0.40, 0.28) | (0.52, 0.52, 0.30) | (0.67, 0.36, 0.31) | (0.58, 0.47, 0.26) |
| WWS-9 | (0.74, 0.28, 0.24) | (0.62, 0.41, 0.29) | (0.57, 0.46, 0.34) | (0.65, 0.38, 0.27) | (0.72, 0.31, 0.23) |
| WWS-10 | (0.56, 0.46, 0.38) | (0.52, 0.50, 0.37) | (0.6, 0.43, 0.32) | (0.63, 0.40, 0.29) | (0.58, 0.47, 0.31) |
| WWS-11 | (0.68, 0.35, 0.26) | (0.71, 0.32, 0.27) | (0.63, 0.40, 0.30) | (0.70, 0.33, 0.26) | (0.68, 0.35, 0.25) |
| WWS-12 | (0.57, 0.49, 0.27) | (0.68, 0.34, 0.24) | (0.49, 0.54, 0.37) | (0.57, 0.48, 0.28) | (0.27, 0.76, 0.28) |
| WWS-13 | (0.67, 0.36, 0.28) | (0.71, 0.33, 0.24) | (0.70, 0.33, 0.26) | (0.58, 0.47, 0.32) | (0.64, 0.39, 0.33) |
| WWS-14 | (0.59, 0.44, 0.39) | (0.69, 0.34, 0.24) | (0.55, 0.48, 0.36) | (0.76, 0.27, 0.23) | (0.53, 0.49, 0.36) |
| WWS-15 | (0.59, 0.44, 0.30) | (0.72, 0.31, 0.24) | (0.52, 0.51, 0.35) | (0.65, 0.38, 0.25) | (0.55, 0.49, 0.35) |
| WWS-16 | (0.58, 0.44, 0.31) | (0.47, 0.56, 0.36) | (0.51, 0.52, 0.34) | (0.62, 0.41, 0.34) | (0.52, 0.52, 0.35) |
| WWS-17 | (0.70, 0.35, 0.21) | (0.54, 0.47, 0.41) | (0.53, 0.51, 0.35) | (0.53, 0.52, 0.30) | (0.63, 0.39, 0.34) |
| WWS-18 | (0.57, 0.46, 0.33) | (0.59, 0.45, 0.30) | (0.65, 0.42, 0.23) | (0.57, 0.46, 0.36) | (0.64, 0.39, 0.30) |
| WWS-19 | (0.61, 0.42, 0.30) | (0.47, 0.60, 0.28) | (0.61, 0.42, 0.30) | (0.60, 0.44, 0.32) | (0.55, 0.48, 0.32) |
| WWS-20 | (0.57, 0.47, 0.32) | (0.64, 0.39, 0.28) | (0.61, 0.43, 0.34) | (0.49, 0.55, 0.34) | (0.53, 0.53, 0.28) |

**Table A7.** Spherical fuzzy average solution.

| Criteria | EC1 | EC2 | EC3 | EC4 | EC5 |
|---|---|---|---|---|---|
| Average solution | (0.66, 0.37, 0.30) | (0.62, 0.42, 0.31) | (0.63, 0.41, 0.29) | (0.67, 0.36, 0.28) | (0.63, 0.41, 0.30) |
| **Criteria** | **EC6** | **EC7** | **EC8** | **EC9** | **EC10** |
| Average solution | (0.62, 0.41, 0.31) | (0.62, 0.42, 0.30) | (0.60, 0.44, 0.31) | (0.61, 0.43, 0.31) | (0.60, 0.44, 0.30) |

**Table A8.** Defuzzied decision matrix and average solution.

| Location | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| WWS-1 | 0.182 | 0.140 | 0.135 | 0.093 | 0.128 | 0.126 | 0.120 | 0.083 | 0.028 | 0.315 |
| WWS-2 | 0.106 | 0.052 | 0.122 | 0.062 | 0.090 | 0.101 | 0.171 | 0.142 | 0.103 | 0.267 |
| WWS-3 | 0.145 | 0.137 | 0.076 | 0.192 | 0.165 | 0.107 | 0.119 | 0.108 | 0.153 | 0.114 |
| WWS-4 | 0.110 | 0.197 | 0.160 | 0.178 | 0.092 | 0.115 | 0.055 | 0.115 | 0.037 | 0.082 |
| WWS-5 | 0.149 | 0.106 | 0.167 | 0.195 | 0.147 | 0.112 | 0.210 | 0.071 | 0.081 | 0.145 |
| WWS-6 | 0.089 | 0.109 | 0.162 | 0.221 | 0.165 | 0.125 | 0.044 | 0.080 | 0.117 | 0.058 |
| WWS-7 | 0.304 | 0.075 | 0.152 | 0.131 | 0.083 | 0.135 | 0.091 | 0.372 | 0.117 | 0.044 |
| WWS-8 | 0.111 | 0.103 | 0.114 | 0.191 | 0.104 | 0.165 | 0.145 | 0.094 | 0.130 | 0.150 |
| WWS-9 | 0.043 | 0.202 | 0.115 | 0.161 | 0.120 | 0.249 | 0.126 | 0.067 | 0.161 | 0.243 |
| WWS-10 | 0.093 | 0.059 | 0.059 | 0.091 | 0.223 | 0.038 | 0.040 | 0.094 | 0.135 | 0.100 |
| WWS-11 | 0.306 | 0.090 | 0.124 | 0.135 | 0.139 | 0.187 | 0.196 | 0.121 | 0.198 | 0.191 |
| WWS-12 | 0.128 | 0.098 | 0.137 | 0.219 | 0.227 | 0.142 | 0.206 | 0.041 | 0.129 | 0.226 |
| WWS-13 | 0.152 | 0.271 | 0.129 | 0.181 | 0.023 | 0.156 | 0.231 | 0.196 | 0.089 | 0.100 |
| WWS-14 | 0.141 | 0.177 | 0.133 | 0.138 | 0.075 | 0.045 | 0.210 | 0.051 | 0.280 | 0.045 |
| WWS-15 | 0.326 | 0.104 | 0.164 | 0.238 | 0.062 | 0.102 | 0.233 | 0.052 | 0.180 | 0.059 |
| WWS-16 | 0.170 | 0.042 | 0.173 | 0.261 | 0.067 | 0.095 | 0.049 | 0.063 | 0.084 | 0.056 |
| WWS-17 | 0.109 | 0.098 | 0.225 | 0.131 | 0.047 | 0.258 | 0.021 | 0.053 | 0.097 | 0.084 |
| WWS-18 | 0.043 | 0.120 | 0.136 | 0.137 | 0.354 | 0.074 | 0.107 | 0.213 | 0.057 | 0.122 |
| WWS-19 | 0.066 | 0.102 | 0.079 | 0.325 | 0.124 | 0.111 | 0.141 | 0.113 | 0.090 | 0.083 |
| WWS-20 | 0.130 | 0.078 | 0.305 | 0.140 | 0.158 | 0.086 | 0.139 | 0.080 | 0.062 | 0.127 |
| Average solution | 0.135 | 0.108 | 0.129 | 0.164 | 0.120 | 0.113 | 0.118 | 0.099 | 0.106 | 0.110 |

**Table A9.** Positive distance from average solution.

| Location | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| WWS-1 | 0.346 | 0.301 | 0.053 | 0 | 0.063 | 0.115 | 0.022 | 0 | 0 | 1.866 |
| WWS-2 | 0 | 0 | 0 | 0 | 0 | 0 | 0.449 | 0.432 | 0 | 1.43 |
| WWS-3 | 0.075 | 0.277 | 0 | 0.169 | 0.371 | 0 | 0.011 | 0.088 | 0.449 | 0.042 |
| WWS-4 | 0 | 0.833 | 0.248 | 0.083 | 0 | 0.02 | 0 | 0.159 | 0 | 0 |
| WWS-5 | 0.1 | 0 | 0.296 | 0.191 | 0.224 | 0 | 0.779 | 0 | 0 | 0.319 |
| WWS-6 | 0 | 0.013 | 0.26 | 0.348 | 0.368 | 0.108 | 0 | 0 | 0.101 | 0 |
| WWS-7 | 1.251 | 0 | 0.182 | 0 | 0 | 0.197 | 0 | 2.749 | 0.107 | 0 |
| WWS-8 | 0 | 0 | 0 | 0.166 | 0 | 0.464 | 0.23 | 0 | 0.227 | 0.366 |
| WWS-9 | 0 | 0.876 | 0 | 0 | 0 | 1.208 | 0.072 | 0 | 0.516 | 1.213 |
| WWS-10 | 0 | 0 | 0 | 0 | 0.859 | 0 | 0 | 0 | 0.279 | 0 |
| WWS-11 | 1.265 | 0 | 0 | 0 | 0.154 | 0.663 | 0.664 | 0.217 | 0.87 | 0.742 |
| WWS-12 | 0 | 0 | 0.066 | 0.334 | 0.892 | 0.262 | 0.748 | 0 | 0.219 | 1.058 |
| WWS-13 | 0.127 | 1.522 | 0.003 | 0.107 | 0 | 0.381 | 0.964 | 0.977 | 0 | 0 |
| WWS-14 | 0.046 | 0.648 | 0.032 | 0 | 0 | 0 | 0.778 | 0 | 1.648 | 0 |
| WWS-15 | 1.413 | 0 | 0.278 | 0.452 | 0 | 0 | 0.979 | 0 | 0.699 | 0 |
| WWS-16 | 0.256 | 0 | 0.342 | 0.594 | 0 | 0 | 0 | 0 | 0 | 0 |
| WWS-17 | 0 | 0 | 0.752 | 0 | 0 | 1.291 | 0 | 0 | 0 | 0 |
| WWS-18 | 0 | 0.112 | 0.057 | 0 | 1.942 | 0 | 0 | 1.151 | 0 | 0.113 |
| WWS-19 | 0 | 0 | 0 | 0.985 | 0.035 | 0 | 0.199 | 0.137 | 0 | 0 |
| WWS-20 | 0 | 0 | 1.369 | 0 | 0.314 | 0 | 0.181 | 0 | 0 | 0.159 |

**Table A10.** Negative distance from average solution.

| Location | EC1 | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 | EC8 | EC9 | EC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| WWS-1 | 0 | 0 | 0 | 0.43 | 0 | 0 | 0 | 0.16 | 0.74 | 0 |
| WWS-2 | 0.215 | 0.52 | 0.048 | 0.624 | 0.248 | 0.106 | 0 | 0 | 0.028 | 0 |
| WWS-3 | 0 | 0 | 0.405 | 0 | 0 | 0.049 | 0 | 0 | 0 | 0 |
| WWS-4 | 0.188 | 0 | 0 | 0 | 0.237 | 0 | 0.535 | 0 | 0.647 | 0.249 |
| WWS-5 | 0 | 0.015 | 0 | 0 | 0 | 0.006 | 0 | 0.286 | 0.235 | 0 |
| WWS-6 | 0.342 | 0 | 0 | 0 | 0 | 0 | 0.626 | 0.192 | 0 | 0.47 |
| WWS-7 | 0 | 0.305 | 0 | 0.203 | 0.306 | 0 | 0.231 | 0 | 0 | 0.604 |
| WWS-8 | 0.181 | 0.043 | 0.117 | 0 | 0.136 | 0 | 0 | 0.048 | 0 | 0 |
| WWS-9 | 0.682 | 0 | 0.105 | 0.016 | 0.006 | 0 | 0 | 0.328 | 0 | 0 |
| WWS-10 | 0.309 | 0.448 | 0.538 | 0.443 | 0 | 0.663 | 0.658 | 0.055 | 0 | 0.088 |
| WWS-11 | 0 | 0.168 | 0.036 | 0.176 | 0 | 0 | 0 | 0 | 0 | 0 |
| WWS-12 | 0.053 | 0.087 | 0 | 0 | 0 | 0 | 0 | 0.583 | 0 | 0 |
| WWS-13 | 0 | 0 | 0 | 0 | 0.807 | 0 | 0 | 0 | 0.155 | 0.092 |
| WWS-14 | 0 | 0 | 0 | 0.159 | 0.379 | 0.605 | 0 | 0.487 | 0 | 0.588 |
| WWS-15 | 0 | 0.035 | 0 | 0 | 0.483 | 0.09 | 0 | 0.473 | 0 | 0.46 |
| WWS-16 | 0 | 0.614 | 0 | 0 | 0.441 | 0.16 | 0.588 | 0.363 | 0.203 | 0.491 |
| WWS-17 | 0.191 | 0.089 | 0 | 0.2 | 0.605 | 0 | 0.818 | 0.462 | 0.087 | 0.239 |
| WWS-18 | 0.682 | 0 | 0 | 0.165 | 0 | 0.339 | 0.09 | 0 | 0.462 | 0 |
| WWS-19 | 0.515 | 0.049 | 0.385 | 0 | 0 | 0.017 | 0 | 0 | 0.147 | 0.24 |
| WWS-20 | 0.038 | 0.272 | 0 | 0.146 | 0 | 0.239 | 0 | 0.194 | 0.413 | 0 |

**Table A11.** The efficiency–sustainability rank of the WWS locations.

| Location | Sustainability Aspect | Efficiency Aspect with the Given Value of Θ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.55 | 0.60 | 0.65 | 0.70 | 0.75 | 0.80 | 0.85 | 0.90 | 0.95 | 1.00 |
| WWS-1 | 8 | 14 | 14 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| WWS-2 | 14 | 11 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 11 |
| WWS-3 | 10 | 12 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 12 |
| WWS-4 | 16 | 10 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 13 |
| WWS-5 | 7 | 15 | 15 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 |
| WWS-6 | 17 | 13 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |

**Table A11.** *Cont.*

| Location | Sustainability Aspect | Efficiency Aspect with the Given Value of Θ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.55 | 0.60 | 0.65 | 0.70 | 0.75 | 0.80 | 0.85 | 0.90 | 0.95 | 1.00 |
| WWS-7 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 |
| WWS-8 | 11 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 6 | 3 |
| WWS-9 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 4 |
| WWS-10 | 20 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 5 |
| WWS-11 | 1 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 6 |
| WWS-12 | 4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| WWS-13 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 7 | 9 |
| WWS-14 | 13 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 7 |
| WWS-15 | 6 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 8 |
| WWS-16 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 |
| WWS-17 | 18 | 18 | 18 | 18 | 18 | 18 | 17 | 17 | 17 | 16 | 16 |
| WWS-18 | 9 | 17 | 17 | 17 | 17 | 16 | 16 | 16 | 16 | 17 | 17 |
| WWS-19 | 15 | 16 | 16 | 16 | 16 | 17 | 18 | 18 | 18 | 18 | 18 |
| WWS-20 | 12 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |

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