Simulation-Based Optimization Integrated Multiple Criteria Decision-Making Framework for Wave Energy Site Selection: A Case Study of Australia

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ABSTRACT
This study aims to develop a novel and robust simulation-based integration framework to identify optimal locations for wave energy projects in Australia. The process of multi-criteria evaluating and selecting locations based on feasible conditions, published numerical data, and linguistic judgments of experts. With this aim in mind, this paper proposes the first combination of Data Envelopment Analysis (DEA) approach, Fuzzy Best-Worst Method (Fuzzy BWM), and Simulation-based Fuzzy Multi-Criteria Interactive Decision-Making method (Fuzzy TODIM). Firstly, the DEA model helps to filter out potentially and highly effective locations from feasible locations. Afterward, Fuzzy BWM is a worthy and effective alternative to Analytic Hierarchy Process (AHP) in weighting criteria. Finally, the simulation-based Fuzzy TODIM method evaluates potential locations, taking into account both the consideration of the criteria interaction and the decision maker’s aversion to loss. Based on the simulation results, the study finds the thresholds of the loss attenuation coefficient that change the ranking of potential locations. Last but not least, to validate the ranking result, the comparison shows that the proposed method’s results have a high degree of similarity with actual wave energy projects in Australia. Accordingly, governments, investors, and institutions can sustainably optimize the efficiency of wave energy projects by applying the proposed model. Moreover, the integrated framework can provide robust solutions to other multiple criteria decision-making problems.

INDEX TERMS Renewable energy, wave energy location, fuzzy sets, simulation, DEA, fuzzy BWM, fuzzy TODIM, decision making.

I. INTRODUCTION
A. BACKGROUND AND MOTIVATION
Energy is one of the leading factors in global industrial and economic development. Fossil fuels have been mankind’s dominant source of energy for decades. However, coal, oil and natural gas are responsible for more than 80% of global CO2 emissions [1]. Depleting fossil reserves and rising prices, especially in the negative impacts of the COVID-19 pandemic, have increased the urgency of renewable energy options. As of 2021, Australia’s economy has the twelfth largest nominal GDP in the world [2]. That is one of the reasons for Australia’s huge energy consumption of up to 6,013.8 petajoule (PJ) in 2020 [3]. To sustainably satisfy energy consumption, the renewable energy industry has grown rapidly in Australia in the last five years. In 2020, statistics show that the share of renewable energy exceeds a quarter of the country’s total energy production for the first time [4]. Through published studies, Australia’s wave energy potential is among the top in the world [5]. Especially on
the southeastern shelf of Australia, the observed time-average wave energy is 25-35 \( \text{kW/m}^{-1} \) [6]. According to forecasts, wave energy could contribute 11\% of Australia’s energy by 2050 [7]. However, because it is considered an expensive renewable energy technology, wave energy projects in Australia have not been properly invested.

To develop this renewable energy sector, the problems of wave energy resources, wave energy technology and wave climates in Australian marine areas have attracted the researchers’ attention. Besides, determining suitable and highly efficient locations for wave energy projects (WEPs) is also an essential research problem. However, multi-criteria location assessments that include economic, social, environmental, and technological factors on wave energy projects in Australia are still lacking as discussed in section II.

B. OBJECTIVES AND NOVELTIES

This study’s objective is to analyze and evaluate locations in the Australian marine area for the WEP’s establishment. The evaluation process includes both quantitative analyzes based on the databases and qualitative analyzes based on linguistics judgments of experts. Because judgments for many real-world problems are difficult to express with exact numbers [8]. Therefore, this study applies the fuzzy theory to describe the experts’ qualitative assessments. As shown in Figure 1, the proposed framework combines the DEA method to select efficient locations, the fuzzy best-worst method (Fuzzy BWM) to determine the weights of the criteria, and the fuzzy TODIM method (abbreviation of Multi-Criteria Interactive Decision-Making in Portuguese) to rank locations. The first stage of the proposed framework is to identify potential locations. There are 25 feasible locations identified by screening through the feasibility conditions (i.e., military area, marine protected area, national prohibited area, distance to shore, wave energy flux). Then, by quantitative analysis of the DEA model, the locations with low efficiency are eliminated. In the second stage, Fuzzy BWM and Fuzzy TODIM are proposed for multi-criteria qualitative assessment of remaining potential locations. The Fuzzy BWM is a novel and powerful weighting method for criteria. The first core advantage of Fuzzy BWM is that it requires fewer pairwise comparisons than the traditional Analytic Hierarchy Process (AHP) method. The second advantage is that the weights of the criteria are determined with optimal consistency of pairwise comparisons via a non-linear programming model [9]. Then, Fuzzy TODIM is a robust and modern choice for ranking locations. This method combines the features of both the Aggregation approach (e.g., AHP, Multi-Attribute Utility Theory) and the Outranking approach (e.g., Elimination et Choix Traduisant la Réalité - ELECTRE, Preference Ranking Organization Method for Enriched Evaluation - PROMETHEE) to the ranking problem. Fuzzy TODIM allows ranking with consideration for the interaction between criteria [10]. Moreover, it incorporates the principle of Prospect theory to rank under the influence of the psychological behavior of decision-makers [11]. In this study, the Fuzzy TODIM method is used in the simulation environment to predict the effects of decision makers’ loss aversion to the ranking results.

The primary novelty research is developing both quantitative and qualitative exploration of potential locations for WEP in Australia. The first comprehensive multi-criteria investigation considers the psychological behavior of decision-makers in determining Australia’s WEP appropriate locations for sustainable development. The secondary novelty of this study is the combination of DEA, Fuzzy BWM, and simulation-based TODIM methods for the first time. These methods have been identified as effective methods for multiple criteria decisions making (MCDM) problems with their advantages. The developed and proposed framework provides an efficient, novel, and powerful tool for similar MCDM problems, especially the selection of locations for WEPs.

The structure of the remaining content includes literature review in section II, methodology in section III, numerical results in section IV. Finally, in section V, this study closes with conclusions and recommendations.

II. LITERATURE REVIEW

For coastal countries, wave energy is an available and inexhaustible source of energy. Besides wind and solar energy, wave energy related investigations have developed rapidly in many regions and countries around the world [12]. The research objectives of scholars, governments, and organizations on wave energy primarily fall into three categories. The first categories focus on technology development and cost reduction for wave energy projects [13]–[16]. The second category targets wave energy source and wave climate investigations with national, regional or global scope [5]–[7], [17]–[21]. The third category is concerned with the problem of locating WEPs to ensure both effectiveness and sustainability. Location optimization is considered as one of the factors that directly influence the effectiveness of WEPs as...
well as the economic, social and environmental conditions in the vicinity [22]. Investigations on the appropriate location for WEPs are developed for several regions can be listed as Europe [16], [23]–[27], Asia [19], [28]–[30] and Australia [22], [31]. To evaluate the effectiveness of locations, the definition of a system of evaluation criteria is the decisive step. This system of criteria is mainly determined based on literature reviews and expert surveys [12]. Most previous studies used criteria related to economic, social, environmental, and technical factors to select WEP locations. According to literature reviews and expert opinion, common criteria for this problem are presented in Table 1.

For wave energy in Australia, wave-climate studies indicate great potential energy from the ocean. The results of the study, conducted by Hughes, M.G. and Heap, A.D., indicate that Australia’s more than 3,000km southern shelf is a huge resource of wave energy. In contrast, the wave energy potential in Australia’s northern marine region is not sufficient to make a significant contribution to the national grid [6]. In 2016, Flocard, F. et al. proposed a geo-spatial evaluation method to identify suitable locations for constructing wave energy farms. This investigation focuses on analyzing locations on the southeastern coast of Australia [22]. In the last few decades, MCDM methods have been a popular tool for the location selection problem of renewable energy problems. Based on the results of systematic review studies, MCDM methods are used in combination to perform two adjacent and distinct tasks. They are determining the weight of the criteria and evaluating the alternatives [12]. In which, the AHP method is most widely used for the task of determining the weight of the criteria [12]. Meanwhile, the TOPSIS [32]–[39], Vlekriterijumsko Kompromisno Rangiranje (VIKOR) [37], [40], ELECTRE [34], [41]–[45], DEA [46]–[48] and other methods [16], [25], [49] are commonly used to evaluate alternatives. Recently, more robust MCDM methods have been developed and introduced for selection and ranking problems. In 2015, for the first time the BWM approach was introduced by Jafar Rezaei [39]. Compared with the AHP method, which is also based on pairwise comparisons, the BWM approach requires less data, but the consistency of comparisons is higher. In later improvements, fuzzy sets were incorporated into the original BWM approach [8], [50], [51]. Another robust and promising candidate for the advancement of MCDM methods is the TODIM approach. This approach was developed long ago for the alternative ranking problems by Gomes and Lima [52]. However, after being strengthened by the principles of prospect theory [11] and fuzzy theory [10], [53]–[56], the results of the TODIM method have become more robust and comprehensive. On the other hand, many studies have used simulation techniques to predict the effect of one or more parameters in multi-criteria calculations. In 2017, Tomas, B. and Dalia, S. applied the Monte Carlo simulation method to the multi-criteria ranking of energy production scenarios [57]. Recently, Devika, K. et al. proposed a hybrid approach between BWM and gray relational analysis (GRA) to select locations for solar energy in Iran. This study also provides comparison results with other MCDM methods via Monte Carlo simulation model.

According to the above discussion, it can be seen that Australia’s ocean energy potentials are enormous. To optimize the wave energy resources, the problem of the site assessment is necessary for the sustainable construction of WEPs. However, there is a lack of research on choosing WEP optimal locations. Regarding the approach, there is no record of the combination of DEA, Fuzzy BWM, and Fuzzy TODIM for this problem. Firstly, the DEA model helps to filter out potentially and highly effective locations from feasible locations. Afterward, Fuzzy BWM is a worthy and effective alternative to AHP in weighting criteria. Finally, the simulation-based Fuzzy TODIM method evaluates potential locations, taking into account both the consideration of the criteria interaction and the decision maker’s aversion to loss.

III. METHODOLOGY
A. DATA ENVIRONMENTAL ANALYSIS
In 1978, Charnes, Cooper and Rhodes developed the first DEA model [58] also known as CCR model based on Farrell’s efficiency production model [59]. In this model, the efficiency of decision-making units (DMUs) is defined as the ratio of weighted outputs to weighted inputs. Based on N inputs and K outputs, the efficiency (e) of M DMU is determined by solving the non-linear programming model as in (1).

\[
\begin{align*}
\text{max } & e_i = \frac{\sum_{k=1}^{K} v_k y_{ki}}{\sum_{j=1}^{N} u_j x_{ji}} \\
\text{s.t. } & \frac{\sum_{k=1}^{K} v_k y_{ki}}{\sum_{i=1}^{M} u_i x_{ji}} \leq 1 \\
& \sum_{j=1}^{N} y_j \geq 0 \quad k = 1, 2, \ldots, K; \\
& \sum_{i=1}^{M} u_i \geq 0 \quad k = 1, 2, \ldots, K; \\
& v_k \geq 0 \quad k = 1, 2, \ldots, K; \\
& x_{ji} \quad j = 1, 2, \ldots, N; \\
& y_{ki} \quad i = 1, 2, \ldots, M. 
\end{align*}
\]

where \(x_{ji}\) and \(y_{ki}\) present the \(j\)th input and \(k\)th output of \(i\)th DMU respectively. Assume \(u_i\) and \(v_k\) present the virtual variables of \(j\)th input and \(k\)th output, respectively. Furthermore, the CCR model proposes values of inputs and outputs that optimize performance using positive slack (\(s^+\)) and negative slack (\(s^-\)) variables as (2) and (3).

\[
\begin{align*}
x_{ji}^* & = e_i x_{ji} - s_j^- & j = 1, 2, \ldots, N; \\
y_{ki}^* & = y_{ki} + s_k^+ & k = 1, 2, \ldots, K; \\
\end{align*}
\]

where \(x_{ji}^*, y_{ki}^*, s_j^-, s_k^+\) present the optimal value of \(x_{ji}, y_{ki}, s_j, s_k\). Thus, the efficiency of \(i\)th DMU is optimal when \(s_j^* = s_k^+ = 0\) and \(e_i = 1\). In 2001, Tone proposed a DEA model that determines the efficiency of DMUs based on slack measurements of inputs and outputs (SBM) [60]. In the non-oriented SBM model, as shown in (4), the 0th DMU (\(x_0, y_0\)) is defined as
TABLE 1. List of common criteria according to literature review.

| Authors            | Wave height | Wind speed | Water depth | Water quality | Distance to shore | Distance to ports | Distance to the power grid | Costs | Population served | Other human activities | Environmental impacts |
|--------------------|-------------|------------|-------------|---------------|------------------|------------------|------------------------|-------|------------------|------------------------|------------------------|
| Nobre, Ana et al. [15] | X          | X          | X           | X             | X                | X                | X                      | X     | X                | X                      | X                      |
| Zubieta, L. et al. [27] | X          | X          | X           | X             | X                | X                | X                      | X     | X                | X                      | X                      |
| Y.-H. Lin et al. [19] | X          | X          | X           | X             | X                | X                | X                      | X     | X                | X                      | X                      |
| Cradden, L. [16]     | X          | X          | X           | X             | X                | X                | X                      | X     | X                | X                      | X                      |
| Flocard, F. et al. [22] | X          | X          | X           | X             | X                | X                | X                      | X     | X                | X                      | X                      |
| Ghosh, S. et al. [23] | X          | X          | X           | X             | X                | X                | X                      | X     | X                | X                      | X                      |
| Abaci, M. M. et al. [31] | X          | X          | X           | X             | X                | X                | X                      | X     | X                | X                      | X                      |
| Vasilces, M. et al. [25] | X          | X          | X           | X             | X                | X                | X                      | X     | X                | X                      | X                      |
| Bolturk, E. et al. [30] | X          | X          | X           | X             | X                | X                | X                      | X     | X                | X                      | X                      |
| Loukogeorgaki, E. et al. [26] | X          | X          | X           | X             | X                | X                | X                      | X     | X                | X                      | X                      |
| Bozejryk, M. E. [29]  | X          | X          | X           | X             | X                | X                | X                      | X     | X                | X                      | X                      |
| Choupin, O. et al. [20] | X          | X          | X           | X             | X                | X                | X                      | X     | X                | X                      | X                      |
| Murat Şan et al. [28] | X          | X          | X           | X             | X                | X                | X                      | X     | X                | X                      | X                      |

TABLE 2. Fuzzy BWM linguistic judgment and consistency indices (CIs).

| Linguistic judgment | TFNs | CIs |
|---------------------|------|-----|
| Equally important (EI) | (1,1,1) | 3.00 |
| Weakly important (WI) | (2/3,1,3/2) | 3.80 |
| Important (I) | (3/2,2,5/2) | 5.29 |
| Very important (VI) | (5/2,3,7/2) | 6.69 |
| Strongly important (SI) | (7/2,4,9/2) | 8.04 |
| Extremely important (EI) | (9/2,5,11/2) | 9.35 |

SBM-efficient if $s_j^* = s_k^* = 0$ and $\theta^* = 1$.

$$\min \theta = \frac{1 - \frac{1}{N} \sum_{i=1}^{N} s_j^{i} \theta_{ij}}{1 + \frac{1}{K} \sum_{k=1}^{K} s_k^{i} \theta_{ki}}$$

s.t. $x_{ij} = \sum_{i=1}^{M} \lambda_i y_{ij} + s_j^{i} j = 1, 2, \ldots, N$

$$y_{ik} = \sum_{i=1}^{M} \lambda_i y_{ki} + s_k^{i} k = 1, 2, \ldots, K$$

$$\lambda_i, \delta_j^i, \delta_k^i \geq 0 \quad \forall i \in M, j \in N, k \in K$$ (4)

B. FUZZY SETS

To support the decision-making process in uncertain conditions, fuzzy sets are used in both criteria weighting and performance evaluation procedures [61], [62].

Definition 1 [50]: Let $\tilde{x} \in F (R)$ be a fuzzy number if:

1. $\tilde{x} = [l, \mu_{\tilde{x}}(t) \geq \beta]$ is a closed interval for any $\beta \in [0, 1]$;
2. There exists $t_0 \in R$ such that $\mu_{\tilde{x}}(t_0) = 1$.

where $R$, $F$ ($R$) and $\mu_{\tilde{x}}(t)$ represent the real number set, fuzzy set, and membership function respectively.

Definition 2 [63]: A triangular fuzzy number (TFN) denoted by $\tilde{x} = (l, m, u)$. Where $l$, $m$ and $u$ represent the smallest, most-likely and largest possible value of TFN $\tilde{x}$. Thus, the membership function of $\tilde{x}$ can be defined as (5).

$$\mu_{\tilde{x}}(t) = \begin{cases} 
\frac{t - l}{m - l}, & l \leq t \leq m \\
\frac{u - t}{m - u}, & m \leq t \leq u \\
0, & \text{otherwise} 
\end{cases}$$ (5)

Then, the fuzzy decision matrix can be expressed as (6):

$$\hat{A} = \begin{bmatrix} 
\tilde{x}_{11} & \tilde{x}_{12} & \ldots & \tilde{x}_{1m} \\
\tilde{x}_{21} & \tilde{x}_{22} & \ldots & \tilde{x}_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
\tilde{x}_{n1} & \tilde{x}_{n2} & \ldots & \tilde{x}_{nm} 
\end{bmatrix}$$ (6)

Because the opinions of experts are difficult to accurately express with exact numbers, linguistic judgments are used to qualitatively compare criteria and evaluate alternatives. The linguistic judgments are converted to the corresponding TFNs to perform the quantitative analysis. Table 2 and Table 3 below describe linguistic judgments and their transformation relationships with TFNs.

Definition 3 [64]: Consider two TFNs $\tilde{x}_1 = (l_1, m_1, u_1)$ and $\tilde{x}_2 = (l_2, m_2, u_2)$. Then we have: $\tilde{x}_1 + \tilde{x}_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$, $\tilde{x}_1 \times \tilde{x}_2 = (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2)$, $\tilde{x}_1 - \tilde{x}_2 = (l_1 - u_2, m_1 - m_2, u_1 - l_2)$, $\tilde{x}_1 \div \tilde{x}_2 = (l_1 \div u_2, m_1 \div m_2, u_1 \div l_2)$ and $\frac{1}{\tilde{x}_j} = \left( \frac{1}{m_j}, \frac{1}{m_j}, \frac{1}{m_j} \right)$. 

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Defination 4 [65]: The TFNs are transformed into a crisp value ($\varphi(\tilde{x})$) as a graded mean as follow:

$$\varphi(\tilde{x}) = \frac{l + 4m + u}{6} \tag{7}$$

Defination 5 [53]: Consider two TFNs $\tilde{x}_1 = (l_1, m_1, u_1)$ and $\tilde{x}_2 = (l_2, m_2, u_2)$. The distance between $\tilde{x}_1$ and $\tilde{x}_2$ ($d(\tilde{x}_1, \tilde{x}_2)$) can be calculated as follow:

$$d(\tilde{x}_1, \tilde{x}_2) = \sqrt{\frac{1}{3} \left[ (l_1 - l_2)^2 + (m_1 - m_2)^2 + (u_1 - u_2)^2 \right]} \tag{8}$$

C. FUZZY BEST-WORST METHOD (FUZZY BWM)

In its first introduction, the best-worst method was applied to determine the weights of the decision-making criteria [9]. Two years later, this method was first extended with fuzzy sets [50]. The fuzzy BWM can be implemented with the following eight main steps:

Step 1: Identify a set of decision-making criteria as $\{C_1, C_2, \ldots, C_m\}$.

Step 2: Determine the best criterion ($C_B$) and the worst criterion ($C_W$) based on the opinion of experts.

Step 3: Determine the fuzzy preference vector ($\tilde{E}_B$) by comparing the best criterion to the remaining criteria. Those comparisons use linguistic judgment and TFNs are mentioned in Table 2. The fuzzy preference vector can be represented as: $\tilde{E}_B = (\tilde{x}_{B1}, \tilde{x}_{B2}, \ldots, \tilde{x}_{Bi}, \ldots, \tilde{x}_{Bm})$. It is obvious that $\tilde{x}_{BB} = (1, 1, 1)$.

Step 4: Determine the fuzzy inverse preference vector ($\tilde{E}_W$) by comparing the remaining criteria to the worst criterion. It can be represented as: $\tilde{E}_W = (\tilde{e}_{W1}, \tilde{e}_{W2}, \ldots, \tilde{e}_{W1}, \ldots, \tilde{e}_{WW})$. $\tilde{e}_{WW} = (1, 1, 1)$.
Step 5: Determine the fuzzy weight ($\tilde{w}_i$) of the criteria by solving the following fuzzy non-linear programming model [50]:

$$\min \max_i \left\{ \frac{\tilde{w}_B}{\tilde{w}_i} - \tilde{e}_{Bi}, \frac{\tilde{w}_i}{\tilde{w}_W} - \tilde{e}_{Wi} \right\}$$

s.t. $\sum_{i=1}^{m} \phi (\tilde{w}_i) = 1$ (9)

where $\tilde{w}_i = (l_i, m_i, u_i)$, $\tilde{w}_B = (l_B, m_B, u_B)$, $\tilde{w}_W = (l_W, m_W, u_W)$, $\tilde{e}_{Bi} = (l_{Bi}, m_{Bi}, u_{Bi})$ and $\tilde{e}_{Wi} = (l_{Wi}, m_{Wi}, u_{Wi})$. Assume that $\delta^* = (h^*, h^*, h^*)$, $\delta = (l^*, m^*, u^*)$, $h^* \leq l^*$, then the fuzzy non-linear programming model can be converted into:

$$\min \delta^*$$

s.t. $\frac{(l_B, m_B, u_B)}{(l_i, m_i, u_i)} - \frac{(l_{Bi}, m_{Bi}, u_{Bi})}{(l_{Wi}, m_{Wi}, u_{Wi})}$

$\leq (h^*, h^*, h^*)$ $i = 1, 2, \ldots, m$

$\frac{(l_i, m_i, u_i)}{(l_W, m_W, u_W)} - \frac{(l_{Wi}, m_{Wi}, u_{Wi})}{(l_{Wi}, m_{Wi}, u_{Wi})}$

$\leq (h^*, h^*, h^*)$ $i = 1, 2, \ldots, m$

$0 \leq l_i \leq m_i \leq u_i$ $i = 1, 2, \ldots, m$

$0 \leq l_B \leq m_B \leq u_B$

$0 \leq l_W \leq m_W \leq u_W$ (10)

By solving the model as (10), the fuzzy weight of criteria ($\tilde{w}_1, \tilde{w}_2, \ldots, \tilde{w}_i, \ldots, \tilde{w}_m$) and the optimized consistency index ($\delta^*$) are determined.

Step 6: Transform the fuzzy weight ($\tilde{w}_i$) into crisp weight ($w_i$) according to (7).

Step 7: Check the consistency ratio (CR) as (11). The closer the CR value is to zero, the better the consistency [66]. Acceptable consistency with CR $\leq 0.1$. The given CI value is according to the linguistic judgments in Table 2.

$$CR = \frac{\delta^*}{CI}$$

(11)

Step 8: Determine the mean of crisp weights with K decision-makers as follow:

$$\bar{w}_i = \frac{1}{K} \sum_{k=1}^{K} w_i \quad i = 1, 2, \ldots, m$$

(12)
The fuzzy TODIM decision matrix can be expressed as (14).

\[
\tilde{s} = \begin{bmatrix}
\tilde{s}_{11} & \tilde{s}_{12} & \cdots & \tilde{s}_{1m} \\
\tilde{s}_{21} & \tilde{s}_{22} & \cdots & \tilde{s}_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
\tilde{s}_{n1} & \tilde{s}_{n2} & \cdots & \tilde{s}_{nm}
\end{bmatrix}
\]  

(14)

\textit{Step 2:} The decision matrix is defuzzed as (7). The crisp TODIM decision matrix can be expressed as (15).

\[
s = \begin{bmatrix}
 s_{11} & s_{12} & \cdots & s_{1m} \\
 s_{21} & s_{22} & \cdots & s_{2m} \\
 \vdots & \vdots & \ddots & \vdots \\
 s_{n1} & s_{n2} & \cdots & s_{nm}
\end{bmatrix}
\]  

(15)

\textit{Step 3:} For each criterion, the distance between fuzzy scores of different alternatives is determined as (8). The distance matrix between fuzzy scores is presented as follows:

\[
d^i = \begin{bmatrix}
 d(\tilde{s}_{11}, \tilde{s}_{11}) & d(\tilde{s}_{11}, \tilde{s}_{21}) & \cdots & d(\tilde{s}_{11}, \tilde{s}_{ni}) \\
 d(\tilde{s}_{21}, \tilde{s}_{11}) & d(\tilde{s}_{21}, \tilde{s}_{21}) & \cdots & d(\tilde{s}_{21}, \tilde{s}_{ni}) \\
 \vdots & \vdots & \ddots & \vdots \\
 d(\tilde{s}_{ni}, \tilde{s}_{11}) & d(\tilde{s}_{ni}, \tilde{s}_{21}) & \cdots & d(\tilde{s}_{ni}, \tilde{s}_{ni})
\end{bmatrix}
\]  

(16)

where \( i = 1, 2, \ldots, m \).

\textit{Step 4:} For each criterion, the gain and loss between different alternatives are determined as (17) for benefit criteria and (18) for cost criteria:

\[
G^i_{ji} = \begin{cases} 
 d(\tilde{s}_{ji}, \tilde{s}_{pi}), & s_{ji} \geq s_{pi} \\
 0, & s_{ji} < s_{pi}
\end{cases}
\]  

(17)

\[
L^i_{ji} = \begin{cases} 
 0, & s_{ji} \geq s_{pi} \\
 -d(\tilde{s}_{ji}, \tilde{s}_{pi}), & s_{ji} < s_{pi}
\end{cases}
\]  

(17)

\[
G^i_{jp} = \begin{cases} 
 0, & s_{ji} \geq s_{pi} \\
 d(\tilde{s}_{ji}, \tilde{s}_{pi}), & s_{ji} < s_{pi}
\end{cases}
\]  

(18)

\[
L^i_{jp} = \begin{cases} 
 -d(\tilde{s}_{ji}, \tilde{s}_{pi}), & s_{ji} \geq s_{pi} \\
 0, & s_{ji} < s_{pi}
\end{cases}
\]  

(18)

where \( i = 1, 2, \ldots, m; j = 1, 2, \ldots, n; p = 1, 2, \ldots, n \).

\textit{Step 5:} Based on the weight of criteria (\( w_j \)), the TODIM relative weights of criteria (\( w'_j \)) are determined based on a reference criterion \( r \) as (19). The reference criterion is the criterion that has the greatest weight or is chosen by the decision-makers.

\[
w'_j = \frac{w_j}{w_r} \quad \text{where } w_r = \{w_j\}
\]  

(19)

where \( i = 1, 2, \ldots, m \).

\textit{Step 6:} The dominance degree matrix for each criterion can be constructed as (20).

\[
\Psi^i_{jp} = \frac{G^i_{jp} w'_j}{\sqrt{\sum_{j'=1}^{m} w'_{j}}} - \frac{1}{\Phi} \sqrt{-L^i_{jp} \left( \sum_{j=1}^{m} w'_j \right)}
\]  

(20)

where \( i = 1, 2, \ldots, m; j = 1, 2, \ldots, n; p = 1, 2, \ldots, n \).

The \( \Psi^i_{jp} \) represents the dominance degree of alternative \( j \) over alternative \( p \) according to criterion \( i \). This dominance degree
degree is affected by the loss attenuation coefficient ($\Phi$) according to Prospect Theory.

**Step 7:** The alternative dominance degree matrix can be calculated as (21):

$$\Psi_{jp} = \sum_{i=1}^{m} \left( \psi_{jp}^i \right)$$  \hspace{1cm} (21)

where $j = 1, 2, \ldots, n$; $p = 1, 2, \ldots, n$.

**Step 8:** The overall TODIM scores of alternatives ($\theta_j$) can be calculated as (22):

$$\theta_j = \frac{\sum_{p=1}^{n} \Psi_{jp} - \min_j \{ \sum_{p=1}^{n} \Psi_{jp} \}}{\min_j \{ \sum_{p=1}^{n} \Psi_{jp} \} - \min_j \{ \sum_{p=1}^{n} \Psi_{jp} \}}$$  \hspace{1cm} (22)

where $j = 1, 2, \ldots, n$.

It can be seen that the overall TODIM scores are in the interval $[0, 1]$. The alternative with a larger overall...
TABLE 6. List of evaluation criteria.

| Factor                  | Criteria                | Description                                                                 |
|-------------------------|-------------------------|-----------------------------------------------------------------------------|
| Technical (C1)          | Wave Height (C11)       | Impact of wave height at the marine area on the energy source               |
|                         | Wind Speed (C12)        | Impact of wind speed at the marine area on the energy source               |
|                         | Manpower availability   | Availability of trained human resources in wave energy                     |
|                         | Water salinity (C14)    | Water characteristics in marine areas that can affect the durability of the |
| Economic (C2)           | Costs (C21)             | Installation, operation, and maintenance costs                             |
|                         | Proximity to residential| Distance to population centers (such as cities, towns) and other renewable   |
|                         | area (C22)              | energy project locations                                                   |
|                         | Tourism Potential       | The potential impacts of WEP on tourism activities                         |
|                         | Fisheries (C24)         | The potential impacts of WEP on fishing activities                         |
| Environmental hazard (C3)| Coastal Erosion (C31)   | The potential impact of coastal erosion on the WEP’s sustainability         |
|                         | Proximity to Marine Reserves (C32)| Distance between WEP and the marine reserves                             |
|                         | Noise impact (C33)      | Noise indirectly affects human activities in the vicinity                  |
|                         | Turbulence (C34)        | The potential impact of turbulent flows on the WEP’s sustainability        |
| Social/Infrastructural (C4)| Proximity to the power grid (C41)| Distance between WEP and the power grids                                |
|                         | Proximity to ports (C42)| Distance between WEP and the seaports                                     |
|                         | Population Served (C43) | Level of the population that is served by WEP energy                        |
|                         | Military activities (C44)| Distance between WEP and areas where military activities are held         |

TABLE 7. Best-against-remains and remains-against-worst linguistic comparison.

| DMs | Best criterion | Technical | Economic | Environmental hazard | Social/Infrastructural |
|-----|----------------|-----------|----------|----------------------|-----------------------|
| 1   | Economic       | (2/3,1,3/2)| (3/2,2,5/2)| (7/2,4,9/2)          | (5/2,3,7/2)          |
| 2   | Environmental hazard | (1,1,1)  | (2/3,1,3/2)| (3/2,2,5/2)          | (5/2,3,7/2)          |
| 3   | Economic       | (2/3,1,3/2)| (1,1,1)  | (1,1,1)              | (3/2,2,5/2)          |
| 4   | Environmental hazard | (5/2,3,7/2)| (2/3,1,3/2)| (3/2,2,5/2)          | (3/2,2,5/2)          |
| 5   | Social/Infrastructural | (3/2,2,5/2)| (7/2,4,9/2)| (2/3,1,3/2)          | (3/2,2,5/2)          |
| 6   | Economic       | (2/3,1,3/2)| (5/2,3,7/2)| (1,1,1)              | (3/2,2,5/2)          |
| 7   | Environmental hazard | (1,1,1)  | (2/3,1,3/2)| (1,1,1)              | (3/2,2,5/2)          |
| 8   | Technology     | (3/2,2,5/2)| (1,1,1)  | (1,1,1)              | (2/3,1,3/2)          |
| 9   | Economic       | (2/3,1,3/2)| (1,1,1)  | (5/2,3,7/2)          | (1,1,1)              |
| 10  | Social/Infrastructural | (1,1,1)  | (7/2,4,9/2)| (2/3,1,3/2)          | (3/2,2,5/2)          |

TODIM score is the better alternative. In other words, the rank of the alternatives is determined based on this overall score.

E. SIMULATION-BASED FUZZY TODIM PROCEDURE

To predict the ranking result under the influence of the decision maker’s psychological behavior, this study develops a simulation environment in which the value of loss attenuation coefficient (Φ) is randomly generated in a given interval. As shown in Figure 2, the number of simulation replications and the continuous uniform distribution of the loss attenuation coefficient are set first. Then, the simulation model will randomly generate a value of the loss attenuation coefficient based on the given uniform distribution. Steps 6, 7, and 8 in the aforementioned fuzzy TODIM process are then performed to determine the overall rating and rank of the alternatives. The ranking results and the corresponding value of the loss attenuation coefficient are recorded in the database. This process is repeated until the pre-set number of simulation replications is reached.

IV. CASE STUDY

To identify marine areas in Australia that are suitable for the development of WEPs, the framework presented in Figure 1 was proposed and applied. The applied framework
TABLE 8. Remains-against-worst linguistic comparison.

| DMs | Worst criterion     | Remains                        |
|-----|---------------------|--------------------------------|
|     |                     | Technical | Economic | Environmental hazard | Social/Infrastructural |
| 1   | Environmental hazard| (7/2,4,9/2) | (3/2,2,5/2) | (1,1,1)              | (3/2,2,5/2)           |
| 2   | Social/Infrastructural| (3/2,2,5/2) | (5/2,3,7/2) | (3/2,2,5/2)          | (1,1,1)              |
| 3   | Social/Infrastructural| (3/2,2,5/2) | (7/2,4,9/2) | (3/2,2,5/2)          | (1,1,1)              |
| 4   | Technical           | (1,1,1)   | (7/2,4,9/2) | (3/2,2,5/2)          | (3/2,2,5/2)          |
| 5   | Economic            | (3/2,2,5/2) | (1,1,1)   | (5/2,3,7/2)          | (3/2,2,5/2)          |
| 6   | Economic            | (5/2,3,7/2) | (1,1,1)   | (3/2,2,5/2)          | (3/2,2,5/2)          |
| 7   | Social/Infrastructural| (3/2,2,5/2) | (3/2,2,5/2) | (3/2,2,5/2)          | (1,1,1)              |
| 8   | Technical           | (1,1,1)   | (3/2,2,5/2) | (3/2,2,5/2)          | (3/2,2,5/2)          |
| 9   | Environmental hazard| (5/2,3,7/2) | (3/2,2,5/2) | (1,1,1)              | (3/2,2,5/2)          |
| 10  | Economic            | (3/2,2,5/2) | (1,1,1)   | (7/2,4,9/2)          | (3/2,2,5/2)          |

TABLE 9. Optimized fuzzy BWM weight and consistency ratio (CR) for main factors.

| DMs | Technical       | Economic       | Environmental hazard | Social/Infrastructural | Optimized consistency index | CI   | CR  |
|-----|----------------|----------------|----------------------|------------------------|-----------------------------|------|-----|
| 1   | (0.458,0.458,0.556) | (0.229,0.229,0.229) | (0.115,0.115,0.115) | (0.173,0.173,0.229) | 0.5007                      | 8.0400 | 6.23% |
| 2   | (0.281,0.281,0.281) | (0.339,0.339,0.441) | (0.225,0.225,0.225) | (0.138,0.138,0.138) | 0.5396                      | 6.6900 | 8.07% |
| 3   | (0.238,0.238,0.353) | (0.346,0.425,0.46)  | (0.185,0.185,0.306) | (0.120,0.120,0.120) | 0.4800                      | 5.2900 | 9.07% |
| 4   | (0.128,0.128,0.154) | (0.424,0.424,0.487) | (0.195,0.195,0.252) | (0.218,0.218,0.282) | 0.3006                      | 6.6900 | 4.49% |
| 5   | (0.229,0.229,0.229) | (0.109,0.109,0.109) | (0.362,0.429,0.429) | (0.244,0.244,0.244) | 0.7444                      | 8.0400 | 9.26% |
| 6   | (0.348,0.379,0.379) | (0.122,0.122,0.122) | (0.216,0.273,0.331) | (0.179,0.235,0.265) | 0.3871                      | 6.6900 | 5.79% |
| 7   | (0.343,0.343,0.343) | (0.229,0.28,0.343)  | (0.195,0.198,0.229) | (0.172,0.172,0.172) | 0.5000                      | 5.2900 | 9.45% |
| 8   | (0.179,0.180,0.180) | (0.232,0.232,0.232) | (0.175,0.248,0.315) | (0.275,0.354,0.354) | 0.5260                      | 5.2900 | 9.94% |
| 9   | (0.296,0.377,0.377) | (0.239,0.239,0.239) | (0.129,0.129,0.129) | (0.269,0.269,0.269) | 0.5838                      | 6.6900 | 8.73% |
| 10  | (0.218,0.248,0.338) | (0.113,0.117,0.117) | (0.337,0.398,0.46)  | (0.227,0.227,0.227) | 0.6056                      | 8.0400 | 7.53% |

The study identifies 25 potential locations for offshore WEPs in Australia.

A. FEASIBILITY CONDITION SCREENING

The locations that are considered infeasible if located in specific maritime zones, which are shown in Figure 3, such as commonwealth marine reserves, national prohibited areas, and defense training/prohibited/practice areas. Besides, WEPs need to be established 25 km or more away from the shore. Distances to shore closer than 25km can lead to negative impacts on other civil and economic activities such as tourism, fishing, and so on [25]. Last but not least, the minimum wave energy flux of potential locations should be greater than or equal to 5 kW/m to ensure efficient exploitation [25]. After reviewing all of the above feasibility conditions according to Australia National Database [68], this study identifies 25 potential locations for offshore WEPs in Australia.

B. POTENTIAL LOCATION DETERMINATION BY DEA

In this section, the DEA method is used to select locations that have high efficiency. Accordingly, there are twenty-five feasible marine coordinates to be considered as decision-making units (DMUs) as shown in Table 4 and Figure 4.
Based on a literature review and expert survey, this study used three inputs and two outputs to identify marine coordinates with optimal efficiency ratios. These inputs and outputs include:

- **Distance from shore (I1):** As discussed above, distance from shore is an important factor for WEPs. This distance if too close can lead to negative ecological and social impacts. But the larger this distance, the greater the project’s operating and maintenance costs. Therefore, coordinates are considered appropriate when the distance to the shore is as short as possible but not below the lower limit (25m).
- **Water depth (I2):** Water depth is also a direct factor affecting the installation, operation and maintenance costs of WEPs. Therefore, projects will be more economically viable when set up at marine coordinates that are smaller in depth.
- **Vessel density (I3):** The bustle of other maritime activities can reduce the efficiency or disrupt the exploitation of WEPs. Thus, the maritime areas with a lower vessel density, the higher the efficiency of the project.
- **Energy consumption (O1):** The primary destination of energy, which is generated from WEPs, is the electricity grid of the adjacent land. The greater the energy demand in this land area, the higher the efficiency of the WEP. Therefore, energy consumption is considered as an output factor.

| DMs | Technical | Economic | Environmental hazard | Social/Infrastructural |
|-----|-----------|----------|----------------------|-----------------------|
| 1   | 0.474     | 0.229    | 0.115                | 0.182                 |
| 2   | 0.281     | 0.356    | 0.225                | 0.138                 |
| 3   | 0.257     | 0.417    | 0.205                | 0.120                 |
| 4   | 0.133     | 0.434    | 0.204                | 0.229                 |
| 5   | 0.229     | 0.109    | 0.418                | 0.244                 |
| 6   | 0.374     | 0.122    | 0.273                | 0.231                 |
| 7   | 0.343     | 0.282    | 0.203                | 0.172                 |
| 8   | 0.180     | 0.232    | 0.247                | 0.341                 |
| 9   | 0.363     | 0.239    | 0.129                | 0.269                 |
| 10  | 0.258     | 0.116    | 0.398                | 0.227                 |
| Mean| 0.289     | 0.254    | 0.242                | 0.215                 |

**TABLE 10.** Crisp weight for main factors.

| Factor | Factor | Criteria | Criteria weight | Overall criteria weight |
|--------|--------|----------|-----------------|------------------------|
| Technical (C1) | 0.289 | Wave Height (C11) | 0.271 | 0.078 |
|         |        | Wind Speed (C12) | 0.302 | 0.087 |
|         |        | Manpower availability (C13) | 0.194 | 0.056 |
|         |        | Water salinity (C14) | 0.233 | 0.067 |
| Economic (C2) | 0.254 | Costs (C21) | 0.300 | 0.076 |
|         |        | Proximity to residential area (C22) | 0.235 | 0.060 |
|         |        | Tourism Potential (C23) | 0.242 | 0.061 |
|         |        | Fisheries (C24) | 0.223 | 0.057 |
| Environmental hazard (C3) | 0.242 | Coastal Erosion (C31) | 0.194 | 0.047 |
|         |        | Distance to Marine Reserves (C32) | 0.247 | 0.060 |
|         |        | Noise impact (C33) | 0.312 | 0.075 |
|         |        | Turbulence (C34) | 0.247 | 0.060 |
| Social/Infrastructural (C4) | 0.215 | Distance to power grid (C41) | 0.269 | 0.058 |
|         |        | Distance to ports (C42) | 0.252 | 0.054 |
|         |        | Population Served (C43) | 0.283 | 0.061 |
|         |        | Military activities (C44) | 0.196 | 0.042 |
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• Wave energy flux (O2): Wave energy flux is the decisive factor to the total energy obtained of WEPs. Locations with wave energy flux are said to be more suitable. Therefore, the wave energy flux is considered as an output factor to evaluate the efficiency of locations.

The values of the inputs and outputs for each possible coordinate were collected from Australian national databases [68], as shown in Table 19 (the appendix). According to the results of the DEA-SBM model, the efficiency of locations is determined and presented in Table 5. The results show that 10 locations achieve absolute efficiency. As shown in Figure 5, these locations are PL-03, PL-04, PL-05, PL-09, PL-10, PL-13, PL-20, PL-21, and PL-22. Ten feasible locations, which are absolutely effective, are considered as potential locations for evaluation and ranking in the next stage of research.

C. POTENTIAL LOCATION RANKING
1) CRITERIA WEIGHTING BY FUZZY BWM
After excluding locations that have not perfect efficiency, the fuzzy best-worst method is used to determine the weights.

### TABLE 12. Aggregated fuzzy decision matrix.

| Location | C11  | C12  | C13  | C14  | C21  | C22  | C23  | C24  |
|----------|------|------|------|------|------|------|------|------|
| PL-03    | (2.7,3.7,4.5) | (1.9,2.4,3.2) | (2.1,2.8,3.7) | (2.7,3.6,4.3) | (2.3,3.2,3.9) | (2.8,3.7,4.2) | (1.6,2.4,3.4) | (1.9,2.8,3.7) |
| PL-04    | (1.7,2,2.3,2) | (1.9,2.7,3.5) | (2.1,3,3.9) | (1.8,2.5,3.4) | (2.3,3,3.7) | (2.4,3.2,4) | (1.4,2.2,3.1) | (1.6,2.4,3.4) |
| PL-05    | (2.5,3.4,4.1) | (2.4,3.3,7) | (1.9,2.7,5.6) | (2.9,3.8,4.4) | (2.2,3.2,4) | (3.9,4.9,5) | (2.9,3.9,4.5) | (2.2,3.9,8) |
| PL-09    | (2.1,2,3,7,3.6) | (2.6,3,5,4,3) | (1.8,2,5,3,4) | (2.8,3,8,4,3) | (2.6,3,6,4,4) | (2.4,3,3,4,1) | (2.4,3,3,2,4) | (2.8,3,7,3) |
| PL-10    | (2.1,2,8,3,6,3) | (2.4,3,2,3,9) | (1.8,2,4,3,2) | (2.2,9,3,7,3) | (2.2,9,3,7,5) | (2.5,3,4,4,1) | (1.8,2,3,3,1) | (2.2,3,2,4) |
| PL-13    | (2.5,3,4,4,1) | (2.3,3,1,3,9) | (2.8,3,6,4,2) | (2.5,3,3,4) | (2.4,3,3,4,1) | (2.2,8,3,7) | (1.9,2,6,3,6) | (2.2,9,3,8) |
| PL-15    | (2.4,3,1,3,7) | (1.7,2,3,3,2) | (2.2,3,3,9) | (1.9,2,6,3,5) | (1.8,2,5,3,5) | (2.8,3,7,4,3) | (1.8,2,7,3,6) | (2.2,3,2,4) |
| PL-20    | (2.6,3,4,4) | (2.3,3,3,7) | (2.1,2,9,3,9) | (1.8,2,6,3,5) | (1.7,2,5,3,5) | (1.9,2,7,3,6) | (1.9,2,7,3,6) | (2.3,3,9) |
| PL-21    | (2.2,3,1,3,8) | (2.1,2,9,3,9) | (1.5,2,2,3,2) | (2.1,2,9,3,8) | (2.7,3,6,4,5) | (2.5,3,4,4,2) | (1.9,2,7,3,7) | (2.1,2,6,3,3) |
| PL-22    | (2.4,3,4,4,2) | (3,4,4) | (2.3,3,3,4,1) | (2.4,3,2,3,9) | (2.5,3,3,4) | (2.2,3,3,8) | (2.1,2,6,3,3) | (2.2,9,3,7,3) |

### TABLE 13. Aggregated crisp decision matrix.

| Location | C31  | C32  | C33  | C34  | C41  | C42  | C43  | C44  |
|----------|------|------|------|------|------|------|------|------|
| PL-03    | (2.3,3,1,3,9) | (2.7,3,5,4,1) | (2.2,3,2,4,1) | (2.2,8,3,6) | (1.8,2,5,3,3) | (2.2,3,1,4) | (2.4,3,1,3,9) | (1.6,2,1,3) |
| PL-04    | (2.1,3,3,8) | (2.8,3,6,4,2) | (1.8,2,5,3,4) | (1.8,2,4,3,3) | (2.8,3,6,4,2) | (2.2,3,1,4) | (2.1,2,7,3,5) | (2.8,3,6,4,1) |
| PL-05    | (2.1,3,3,8) | (1.7,2,1,3) | (2.3,3,9) | (1.9,2,9,3,7) | (1.7,2,5,3,5) | (2.8,3,8,6) | (2.2,3,1,4) | (2.3,2,4) |
| PL-09    | (1.7,2,3,3,3) | (2.1,2,9,3,7) | (2.8,3,6,4,1) | (2.3,2,4,1) | (2.4,3,3,4,1) | (1.8,2,3,3,2) | (1.9,2,8,3,7) | (2.2,8,3,6) |
| PL-10    | (2.3,2,2,3,9) | (1.9,2,6,3,4) | (1.7,2,4,3,4) | (2.9,3,8,4,4) | (1.9,2,8,3,8) | (2.5,3,4,4,2) | (2.8,3,6,4,2) | (3,4,4) |
| PL-13    | (2.9,3,8,4,4) | (2.2,8,3,5) | (2.2,8,3,7) | (2.6,3,4,4) | (1.7,2,6,3,4) | (2.2,3,2,4,1) | (2.4,3,1,3,9) | (2.8,3,6,4,2) |
| PL-15    | (2.2,8,3,6) | (1.9,2,6,3,4) | (2.8,3,7,4,4) | (2.2,8,3,7) | (2.5,3,3,4) | (2.4,3,1,3,9) | (2.5,3,4,2) | (1.9,2,6,3,5) |
| PL-20    | (2.8,3,6,4,1) | (2.6,3,4,4,1) | (2.7,3,7,4,4) | (2.2,5,3,3) | (2.2,3,3,7) | (1.9,2,8,3,6) | (2.8,3,7,4,3) | (1.8,2,5,3,4) |
| PL-21    | (2.3,3,3,4,1) | (2.5,3,3,4,2) | (2.3,3,1,3,8) | (2.8,3,8,4,5) | (2.7,3,6,4,2) | (1.7,2,6,3,5) | (2.5,3,3,4,2) | (2.3,2,3,4,1) |
| PL-22    | (2.9,3,9,4,6) | (2.3,3,2,4) | (2.4,3,2,4) | (1.7,2,6,3,5) | (2.2,3,1,3,8) | (2.3,3,2,4) | (2.5,3,4,4,1) | (2.5,3,3,4,1) |
of the criteria. There are four main factors to be considered including technical (C1), economic (C2), environment hazard (C3), and Social/Infrastructural (C4). They are divided into 16 evaluation criteria as described in Table 6.

The weight determination procedure for the four main factors is presented as follow:

- A group of decision makers is composed of ten experts to define the best and worst criteria. Then, linguistic comparisons were made and converted to TFNs according to their knowledge and opinions as described in Table 7 and Table 8.
- By solving the non-linear programming model (10), the optimal fuzzy weights and consistency ratios of the four main factors are determined as shown in Table 9.
- As shown in Table 10, fuzzy weights are converted to crisp weights according to equation (7).

According to the above results, the comparisons have an acceptable consistency (CR ≤ 10%). Therefore, the Fuzzy BWM procedure provides reasonable results. This procedure is similarly repeated for the other criteria afterward. The synthetic results of the fuzzy BWM method are presented in Table 11. As can be seen in Figure 6, the technical (C1) and the Economic (C2) have a higher weight than the other two factors. However, the weight difference between the main factors is not too large. For the criteria, wind speed, wave height and costs are the most weighted criteria with the influence of 8.74%, 7.83% and 7.62% respectively.

| Location | PL-03 | PL-04 | PL-05 | PL-09 | PL-10 | PL-13 | PL-15 | PL-20 | PL-21 | PL-22 |
|----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| PL-03    | 0.000 | 1.283 | 0.311 | 0.850 | 0.812 | 0.311 | 0.603 | 0.342 | 0.606 | 0.300 |
| PL-04    | 1.283 | 0.000 | 0.981 | 0.436 | 0.476 | 0.981 | 0.719 | 0.981 | 0.688 | 0.988 |
| PL-05    | 0.311 | 0.981 | 0.000 | 0.548 | 0.507 | 0.000 | 0.294 | 0.082 | 0.300 | 0.082 |
| PL-09    | 0.850 | 0.436 | 0.548 | 0.000 | 0.058 | 0.548 | 0.294 | 0.548 | 0.265 | 0.560 |
| PL-10    | 0.812 | 0.476 | 0.507 | 0.058 | 0.000 | 0.507 | 0.252 | 0.507 | 0.216 | 0.520 |
| PL-13    | 0.311 | 0.981 | 0.000 | 0.548 | 0.507 | 0.000 | 0.294 | 0.082 | 0.300 | 0.082 |
| PL-15    | 0.603 | 0.719 | 0.294 | 0.294 | 0.252 | 0.294 | 0.000 | 0.271 | 0.129 | 0.337 |
| PL-20    | 0.342 | 0.981 | 0.082 | 0.548 | 0.507 | 0.082 | 0.271 | 0.000 | 0.311 | 0.163 |
| PL-21    | 0.606 | 0.688 | 0.300 | 0.265 | 0.216 | 0.300 | 0.129 | 0.311 | 0.000 | 0.311 |
| PL-22    | 0.300 | 0.988 | 0.082 | 0.560 | 0.520 | 0.082 | 0.337 | 0.163 | 0.311 | 0.000 |

| Criteria | C11 | C12 | C13 | C14 | C21 | C22 | C23 | C24 |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|
| BWM weight | 0.078 | 0.087 | 0.056 | 0.067 | 0.076 | 0.06 | 0.061 | 0.057 |
| TODIM relative weight | 0.896 | 1.000 | 0.643 | 0.771 | 0.872 | 0.682 | 0.702 | 0.646 |

| Criteria | C31 | C32 | C33 | C34 | C41 | C42 | C43 | C44 |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|
| BWM weight | 0.047 | 0.060 | 0.075 | 0.06 | 0.058 | 0.054 | 0.061 | 0.042 |
| TODIM relative weight | 0.537 | 0.683 | 0.862 | 0.682 | 0.662 | 0.618 | 0.697 | 0.483 |
2) OVERALL RANKING BY FUZZY TODIM

After determining the weights of the criteria in the above section, the Fuzzy TODIM method is used to evaluate and rank 10 potential locations. The hierarchy of the potential location multi-criteria ranking problem is shown in Figure 7. Firstly, decision makers evaluate locations according to each criterion using linguistic terms in Table 3. The linguistic assessments from different decision makers are converted into TFNs and aggregated into a fuzzy decision matrix according to (13), as can be seen in Table 12. Then, the fuzzy decision matrix is transformed into a crisp decision matrix according to (7) as shown in Table 13. Subsequently, the distance between the location’s fuzzy evaluation scores according to each criterion is determined according to (8). An example of the distance between fuzzy evaluation scores of locations according to the wave height criterion (C11) is described in Table 14.

In the next step, the criterion with the highest weight is wind speed (C12) selected as the reference criterion. Based on this reference criterion, the relative weights TODIM are determined according to (19) as shown in Table 15. As mentioned in (20), the dominance degree matrix between locations according to each criterion is determined based on crisp decision-making matrix, distance matrices and relative

### TABLE 17. Overall dominance degree matrix ($\phi = 20$).

| Location | PL-03  | PL-04  | PL-05  | PL-09  | PL-10  | PL-13  | PL-15  | PL-20  | PL-21  | PL-22  |
|----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| PL-03    | 0.0000 | 0.5162 | -0.0416| 0.0185 | -0.1257| -0.6556| 0.0501 | -0.3388| -0.3042| -0.9432|
| PL-04    | -0.0418| 0.0000 | -0.5826| -0.4284| -0.6757| -1.1120| -0.1289| -0.2058| -0.8113| -1.1110|
| PL-05    | 0.4018 | 1.1680 | 0.0000 | 0.3941 | -0.2625| -0.7673| 0.6184 | 0.4298 | 0.2369 | -0.9780|
| PL-09    | 0.5126 | 1.0050 | 0.0840 | 0.0000 | 0.3116 | 0.0932 | 0.3560 | 0.4219 | -0.1664| -0.5482|
| PL-10    | 0.6486 | 1.1320 | 0.7514 | 0.1678 | 0.0000 | 0.2523 | 0.4835 | 0.3117 | 0.0164 | -0.4771|
| PL-13    | 1.0450 | 1.6540 | 1.1010 | 0.3774 | 0.1684 | 0.0000 | 0.9974 | 0.7773 | 0.3055 | -0.3537|
| PL-15    | 0.3996 | 0.6286 | -0.0886| 0.1878 | -0.0215| -0.4868| 0.0000 | 0.2146 | -0.2193| -0.4135|
| PL-20    | 0.8287 | 0.6993 | 0.0074 | 0.1259 | 0.1571 | -0.3833| 0.1479 | 0.0000 | 0.4457 | -0.6683|
| PL-21    | 0.7868 | 1.3180 | 0.2696 | 0.6043 | 0.3946 | 0.1152 | 0.7008 | 0.0178 | 0.0000 | -0.2591|
| PL-22    | 1.3760 | 1.6740 | 1.4240 | 1.0160 | 0.9816 | 0.6787 | 0.9272 | 1.0780 | 0.7287 | 0.0000 |

### FIGURE 8. Overall dominance degree ($\phi = 20$).

### TABLE 18. Fuzzy TODIM result ($\phi = 20$).

| Location | Overall Fuzzy TODIM score | Fuzzy TODIM Rank |
|----------|---------------------------|------------------|
| PL-03    | 0.2185                    | 9                |
| PL-04    | 0                         | 10               |
| PL-05    | 0.4231                    | 7                |
| PL-09    | 0.4784                    | 5                |
| PL-10    | 0.5597                    | 4                |
| PL-13    | 0.7456                    | 2                |
| PL-15    | 0.3537                    | 8                |
| PL-20    | 0.4311                    | 6                |
| PL-21    | 0.6038                    | 3                |
| PL-22    | 1                         | 1                |
TABLE 19. DEA model’s inputs and outputs data.

| Location | Latitude | Longitude | Distance from shore (Km) | Water depth (m) | Vessel Density (Km traversed of vessels more than 24 meters long) | Energy consumption (kWh) | Wave energy flux (kW/m) |
|----------|----------|-----------|--------------------------|----------------|---------------------------------------------------------------|------------------------|------------------------|
| PL-01    | -14.57295| 141.01501 | 57.44                    | 35             | 13                                                            | 4760                   | 5.36                   |
| PL-02    | -13.83541| 144.34937 | 81.08                    | 246            | 286                                                           | 5442                   | 7                      |
| PL-03    | -11.54462| 143.23151 | 43.17                    | 27             | 10                                                            | 5442                   | 4.14                   |
| PL-04    | -16.05109| 145.75562 | 32.42                    | 29             | 131                                                           | 6289                   | 9.01                   |
| PL-05    | -18.14063| 146.76636 | 54.87                    | 25             | 133                                                           | 7135                   | 7.67                   |
| PL-06    | -23.54385| 152.08374 | 71.56                    | 55             | 341                                                           | 4960                   | 7.88                   |
| PL-07    | -38.14320| 148.15063 | 40.34                    | 54             | 170                                                           | 4241                   | 7.53                   |
| PL-08    | -40.12849| 146.25000 | 111.56                   | 81             | 207                                                           | 5381                   | 12.71                  |
| PL-09    | -38.57931| 142.31689 | 25.91                    | 54             | 198                                                           | 6188                   | 55.84                  |
| PL-10    | -38.28670| 141.02188 | 26.79                    | 88             | 215                                                           | 6206                   | 60.5                   |
| PL-11    | -36.39476| 139.28467 | 39.55                    | 46             | 2                                                             | 5159                   | 42.71                  |
| PL-12    | -35.02550| 135.29256 | 32.71                    | 101            | 51                                                            | 4911                   | 59.11                  |
| PL-13    | -36.45443| 139.35883 | 37.76                    | 44             | 1                                                             | 5159                   | 42.34                  |
| PL-14    | -34.31622| 134.97253 | 32.8                     | 76             | 3                                                             | 4911                   | 45.21                  |
| PL-15    | -32.24997| 132.35779 | 27.91                    | 63             | 0                                                             | 5137                   | 36.95                  |
| PL-16    | -32.36604| 128.10059 | 35.22                    | 41             | 1                                                             | 4249                   | 30.36                  |
| PL-17    | -34.31622| 122.64587 | 47.2                     | 80             | 1                                                             | 3355                   | 43.71                  |
| PL-18    | -34.75515| 118.93799 | 27.58                    | 64             | 39                                                            | 4067                   | 30.75                  |
| PL-19    | -29.48264| 114.17816 | 76.45                    | 172            | 272                                                           | 4336                   | 56.99                  |
| PL-20    | -43.14108| 145.39856 | 26.31                    | 249            | 15                                                            | 4329                   | 83.51                  |
| PL-21    | -43.89789| 146.89819 | 29.67                    | 164            | 10                                                            | 4817                   | 83.53                  |
| PL-22    | -43.61222| 147.68097 | 32.59                    | 138            | 4                                                             | 5576                   | 61.62                  |
| PL-23    | -41.57847| 144.21753 | 36.89                    | 478            | 8                                                             | 4585                   | 78.58                  |
| PL-24    | -42.16748| 144.81079 | 39.41                    | 166            | 9                                                             | 5645                   | 79.07                  |
| PL-25    | -38.58253| 147.74414 | 50.79                    | 61             | 161                                                           | 4241                   | 8.82                   |

TODIM weights. Table 16 presents the dominance degree matrix according to the wave height criterion (C11) with the chosen loss attenuation coefficient of 20 ($\Phi = 20$). By similar calculations, the dominance degree matrices of all criteria are determined. Then, these dominance degree matrices are aggregated into the dominance degree overall matrix according to (21) as can be seen in Table 17 and Figure 8.

Finally, the overall Fuzzy TODIM score, and the rank of each location are determined according to (22) as shown in Table 18 and Figure 9. According to the results, with the loss attenuation coefficient is 20, the high-ranking locations are in the marine regions of southeastern Tasmania (PL-22, PL-21), southeastern South Australia (PL-13), and southwestern Victoria (PL-09, PL-10). In contrast, locations in northeastern Queensland (PL-03, PL-04, PL-05), although feasible and potential, are rated and ranked lower.

To evaluate more objectively and predict the effects of the decision maker’s psychological behavior on the evaluation results, the above Fuzzy TODIM procedure was performed in a simulation environment with 10,000 replications. In each replication, the value of the loss attenuation coefficient ($\Phi$) is randomly generated according to the uniform distribution.
By analyzing the simulation results database, this study finds some thresholds of $\Phi$ at which the rank of locations changes. These thresholds are presented in the following vector.

$$\Omega = (4.253, 8.811, 11.140, 40.230, 66.710)$$

Accordingly, the ranking of locations changes when the value of $\Phi$ fluctuates in the interval [4.253, 66.710]. As shown in Figure 10, rank shuffle only occurs for locations PL-05, PL-09, PL-10, and PL-20. Therefore, this study classifies locations into three groups as Figure 11. In which, there are two groups of locations that are not influenced by the psychological behavior of the decision maker. The Group A, which includes the three highest-ranking locations, is PL-22, PL-13 and PL-21. In contrast, the Group C, consisting of PL-03, PL-04 and PL-15, is at the bottom of the rankings. The rest, locations PL-05, PL-09, PL-10 and PL-20 are classified in group B. Of these, the rank of PL-09 is proportional to the value of the loss attenuation coefficient. In other words, the smaller the decision makers’ aversion to loss, the more potential the PL-09 location becomes. Contrastingly, the potential level of location PL-10 and PL-20 is inversely proportional to the value of the loss attenuation coefficient. Unlike all, PL-05’s rank is sensitive to the decision maker’s psychological behavior.

V. RESULTS VALIDATION

A. VERIFICATION WITH EXISTING WEP IN AUSTRALIA

To test the robustness of the solution provided by the proposed framework, comparing the results with the locations of existing wave energy projects is implemented. The proposed framework’s ranking results show that the top three are locations in southeastern Tasmania (PL-22 and PL-21) and southwestern Victoria (PL-13). It can be seen that these are also locations that have been interested in The Australian Renewable Energy Agency (ARENA) in developing ocean energy projects as depicted in Figure 12.

B. COMPARISON WITH OTHER MCDM METHODS

This study compared the ranking results of Fuzzy TODIM method with Fuzzy SAW and Fuzzy TOPSIS methods. As shown in Table 20, the comparison results show that location PL-22 and PL-04 have the highest and lowest rank.
respectively. Meanwhile, locations PL-21, PL-13 and PL-09 belong to the group with high rankings according to the results of all three methods. This shows that the proposed method provides robust solutions to the ranking problems.

VI. CONCLUSION

The objective of this study was to identify optimal locations for WEPs in the Australian marine area. First of all, twenty-five, feasible locations are determined based on the feasible conditions. Afterward, ten potential locations, which had absolute efficiency, were selected based on the quantitative analysis of the DEA model. Subsequently, a system of qualitative evaluation criteria and linguistics judgments is defined by experts. The optimal weight of the criteria is then determined by the non-linear programming model of the Fuzzy BWM approach. Finally, the ranking of potential locations is determined by the simulation-based Fuzzy TODIM method. The main achievements, including contributions, may be summarized as follows:

- Developed and proposed for the first time a novel MCDM that combines the best of the DEA approach, the Fuzzy BWM approach, and the Simulation-based Fuzzy TODIM method.
- Research results show that wind speed, wave height, and costs are the most important criteria according to experts.
- Potential locations for the installation of wave energy projects were evaluated, ranked, and classified through a novel MCDM framework.
- Analyze the impact of the decision maker’s psychologi- cal behavior on the ranking results. From there, forecasts about the change of location rankings are provided.
- The results provided by the proposed framework pass the validation test with a degree of similarity with existing ocean energy projects in Australia.

For future studies, time-series analyses that involve changes in wave climate can ensure the sustainability of wave energy projects.

APPENDIX

See Table 19

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