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OFFSHORE PORT ALLOCATION AND INVESTMENT: AN OPTIMIZATION FRAMEWORK

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Abstract. *Appropriate port location selection is critical to achieve the competitiveness and effectiveness of transportation, distribution, and the entire global supply chain and to bolster the local, regional, and national economies. The objective of this study is to develop a new framework to select the optimal location for the offshore port. The framework includes multicriteria decision-making (MCDM) methods along with experts' judgment and a simulation-based model of the facility's performance. At first, the Rough Analytical Hierarchy Process (AHP) and Rough Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) are utilized to preliminarily prioritize the alternative locations. After that, the port performance of selected locations with their corresponding transport distances over the lifetime of the project is assessed via simulation-based experiments. Finally, life cycle costing (LCC) is performed for the final assessment of each port location. The proposed framework is examined for Cua Lo Petrol Base in Vietnam as a case study. The result of the study indicated that the optimal location unveiled by simulation experiments is not always the first-ranking location based on the MCDM. The outcome of this study will assist port and marine investors to find the optimum location for port planning in terms of technical and economic viewpoints.*

Keywords*: Offshore mooring, optimal location, maritime simulation, AHP, TOPSIS, cost-benefit analysis.*

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1. Introduction

Offshore ports are an indispensable part of marine industry for cargo transport and handling services. Offshore ports are extremely important from strategic and economic perspectives as they facilitate exports and imports of any country by connecting geographical locations (Song & Parola, 2015). Today, by volume, about 80% World trade and 70% in value is handled through seaports (UNCTAD, 2021). In other words, seaport plays a vital part in multimodal transport network for economic developments of countries. Offshore ports foster local, regional, and national economies and boost firm's or organization's competitiveness and effectiveness along the entire global supply chain (Mira, Choong, & Thim, 2019). As the port is a critical node of export and import for cargo transportation and distribution, the proper location selection for an offshore port is not only associated with the operations and competitiveness of a country's foreign trade but also highly connected to the development of the country's economy (Jiang, Li, & Shen, 2018).

Offshore port system consists of mooring facilities and transportation means. The mooring facilities are often located far away from shore, where vessels can be berthing, mooring, and cargo handling activities (Ablanedo-Rosas et al., 2010). The transportation means between the mooring facilities, and terminals (usually located onshore) can be either continuously (belt conveyor, pile lines, etc.) or discontinuously (barge, truck, etc.). The farther facilities located from the shoreline, the lesser dredging required for initial and maintenance constructions of the water areas, and environmental impacts are therefore minimized, but construction and operation costs for the facilities and transportation means might be increased, and harder weather attacks to the port activities. The Hadera Port (Yaron et al., 1982) constructed at open sea, as shown in Fig.1, is a good example of the offshore port. Finding an optimal location of the mooring facility system have been an essential problem and practical issues of the port and marine industries (FWG, 2010; JICA, 2015; JPC, 2015, 2016; PEL, 2009).

Figure 1. Open water terminal at Hadera, Israel

The problem of deciding the ideal location among several choices is pertinent in many fields of social-economic activities such as logistics, marketing, capital investments, construction, location of facilities, hospitality management, (Kabir, Sadiq, & Tesfamariam, 2014; Krylovas, Zavadskas, & Kosareva, 2016; Lee & Yang, 2018) in which multicriteria decision-making (MCDM) has often been considered as an effective tool. Concerning MCDM application in the port-related wind industry and port investment sectors, the literature abounds with recent material relating to the implementation of MCDM to wind farm location selections (Akbari et al., 2017; Mytilinou & Kolios, 2017; Mytilinou, Lozano-Minguez, & Kolios, 2018), port choices (Lam & Dai, 2012; Wang & Yeo, 2019; Wiegmans, Hoest, & Notteboom, 2008; Yeo et al., 2014), and port planning and investments (Gogas, Papoutsis, & Nathanail, 2014; Zavadskas, Turskis, & Bagočius, 2015). Most of these studies mainly focus on the infrastructure, physical conditions, transport networks, and investment costs with a large-scale logistics system for short-term study; they rarely consider the factors about the port's performance for a long-term operation project.

Therefore, the primary objective of this study is to develop a new framework to identify the optimal location for the offshore port. In this paper, we combined the Rough Analytical Hierarchy Process (AHP) and Rough Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methods for overall assessment of the possible port locations, a simulation-based model for investigation of the port performance for the selected candidates, and cost strategy analysis to assist port industry investors for port planning in term of the economical viewpoint. Rough set theory is excellent mathematical method for the evaluation of a vague description or expression that is ambiguous and uncertain (Sharma, Kumari, & Kar, 2018, 2021; Sharma et al., 2022). To the best of our knowledge, such studies have been not found in the literature.

The following sections discus how the proposed framework applied to the assessment of the port location alternatives based on the above design conditions and results of the formulation study. The literature review is given in Section 2. In Section 3, we demonstrate the study area and proposed methodology. Section 4 provides a basis for understanding of MCDM methods and simulation model for the underlying problem. The results of the proposed study are discussed in Section 5. Finally, Section 6 highlights the conclusions of this study.

2. Literature Review

As an interface connecting sea and inland traffic, a seaport is an integrated platform, serving as the basis for production, logistics, information transmission and international trade, as well as a springboard for the economic development of inland. To fully realize these functions, a seaport must be able to receive large ships, satisfy a multi-mode of transport, ship operator and port investor requirements, and other related parties effectively and efficiently (Lam & Dai, 2012)v. Free trade and enhanced competition in maritime transport have resulted the need of performance measurement and monitoring of port operations (Lozano, 2009; Sanchez, Ng, & Garcia-Alonso, 2011). Because of the high investment and time consumption, the port performance factors identification has always been an vital issue not only for the port agency but also for the regional and national port transportation planning (Gök-Kısa, Çelik, & Peker, 2022).

2.1. Applied approaches to determining the port performance factors

There is a wide range of approaches to determining the port performance when it comes to the problem of port location choices and investments. The choice of each approach depending on many issues, of which some key factors are the study purpose, project budget, accuracy requirement, and the availability of data. The most cited approaches are found to be MCDM in which AHP and fuzzy logic are more frequently used (Akbari et al., 2017; Guy & Urli, 2006).

Some others applied mathematical modeling solely or with the aid of MCDM to deal with more complicated problems (Gök-Kısa et al., 2022). While statistical analysis approach often involves the direct measurement of port performance factors through data collection, interviews, and surveys (Rezaei et al., 2018). Table 1 provides an overview of the most frequently cited approaches in the literature for each group separately.

Table 1. Most cited approaches for from perspective of port choices and investments

Applied method	Model	Study purpose	Authors
Modeling approach	Dynamic and linear programming	Optimal location selection for container port development investment	(Koh, 2001)
	Linear programming	Optimal site selection for container transshipment activity and port location	(Baird, 2006)
	Fuzzy evidential reasoning (FER)	Port selection for shipping lines in an uncertain environment	(Yeo et al., 2014)
	Cost modeling	Port competition modeling from transport chain perspective	(Song et al., 2016)
	Data envelopment analysis	Port performance factors evaluation	(Ateş et al., 2013; Lee & Lam, 2015; Wang, Huo, & Ortiz, 2015; Wu, Liang, & Song, 2010)
	Simulation modeling	On-shore power supply allocation strategy from green terminal perspective	(Peng et al., 2019)
MCDM	Fuzzy logic	Selecting an optimal location of transshipment container port	(Chou, 2007)
	Fuzzy logic	Optimal investment on port development from national investment perspective	(Allahviranloo & Afandizadeh, 2008)
	Fuzzy logic	Deep-water port selection in Eastern Baltic Sea	(Zavadskas et al., 2015)
	Fuzzy logic	Selecting a transshipment terminal	(Kadaifci et al., 2019)
	Linear programming	Port selection from shippers and/or carriers perspectives	(Lam & Dai, 2012)
	TOPSIS	Optimizing offshore wind farm locations for deployment	(Mytilinou et al., 2018)
	AHP	Installation, operation, and maintenance stages of offshore wind projects	(Akbari et al., 2017)
	AHP	Measurement of port performance in the context of port choice	(Rezaei et al., 2019)
	AHP	Measurement of criteria and business attractiveness for North-European ports	(Nazemzadeh & Vanelslander, 2015)
	TOPSIS, additive ratio assessment (ARAS)	Evaluating the port performance for selection	(Gök-Kısa et al., 2022)
	CRITIC (criteria importance through inter-criteria correlation)	Ro-Ro marine port selection process with a case study in black sea region	(Görçün & Küçükönder, 2021)
	Cost modeling AHP, TOPSIS	Selecting optimal offshore wind farm location	(Akbari et al., 2017; Mytilinou & Kolios, 2017; Mytilinou et al., 2018)
	AHP and Fuzzy logic	Selecting transshipment hub port for shipping carriers	(Wang & Yeo, 2019)
Statistic analysis	Data collection	Port selection for an application to the Montreal-New York alternative	(Guy & Urli, 2006)
	Survey, investigation	Port and terminal selection by deep-sea container operators	(Wiegmans et al., 2008)
	Questionnaire survey	Investigation of major attributes for determining port attractiveness for port selection	(Sanchez et al., 2011)
	Survey, interview, investigation	Environmental performance indicators identification for sustainable port development	(Puig, Wooldridge, & Darbra, 2014)

	Survey, interview	Port selection in Germany based on customer survey	(Lin & Wang, 2019)

2.2. Port performance factors

Port performance factor is at the core of the evaluation for new port choice and development projects. Various studies have been conducted to determine the factors of port performance. Yeo et al. (2010) identified several strategic components under seven principal factors, which impact the port attractiveness. These seven principal factors are hinterland condition, port service, convenience, availability, regional center, logistics costs, and interconnectivity. The most recognized factors regarding port location choices and investments are port charges and logistic costs which consist of port dues, pilot costs, towage, terminal charges, and storage costs (Nazemzadeh & Vanelslander, 2015; Yeo et al., 2014). Some others reveal that the port efficiency and characteristics are the most competent factor (Kadaifci et al., 2019; Rezaei et al., 2018; Tijan et al., 2022). The efficiency of sea-port operations is identified by the time of a ship's stay in a port (including both handling and waiting times) which is mainly affected by weather conditions and availability of the mooring facilities, quality of service to inland transport vehicles, and speed of cargo handling. Akbari et al. (2017) applied AHP for assessment of the port operation taking the physical characteristics of a port, including water depth, subsoil conditions, among others. Other factors but less cited are customs procedure efficiency, port reputation, and information and communication technology systems also considered in studying port competitiveness (Tijan et al., 2022; Wiegmans et al., 2008). Table 2 provides a list of the most relevant performance factors and methods classified each study purpose. The methods are sorted from the most frequently cited to less according to the authors' assessment. The most important factors have been considered in this study, except geographical location.

Table 2. Classification of applied methods by area of application and port performance factors

Factors	**Area of application**				
	Port investment & development	Port choice	Wind farm installation related port	Port layout and location planning	This study
Port efficiency (ship waiting times, operational hours, productivity)	Mat. modeling Fuzzy AHP, TOPSIS Statistic	AHP Fuzzy Modeling Statistic	AHP, TOPSIS Modeling Fuzzy Statistic	Fuzzy AHP Statistic	Simulation modeling and MCDM
Operation costs (port charge, maintenance, pilotage)	Cost modeling AHP, TOPIS Fuzzy	AHP Cost modeling Fuzzy	AHP, TOPIS Fuzzy Cost modeling	Fuzzy AHP, TOPIS Cost modeling	Cost modeling
Port characteristics (number of berths, water depth, ship handling)	Modeling Fuzzy AHP, TOPSIS Statistic	AHP, TOPSIS Fuzzy Modeling Statistic	AHP, TOPSIS Modeling Fuzzy Statistic	Modeling Fuzzy AHP, TOPSIS Statistic	Simulation modeling and MCDM
Interconnectivity of port (sailing frequency, shipping service)	AHP, TOPIS Fuzzy Statistic	Modeling AHP, TOPIS Fuzzy Statistic	Modeling AHP, TOPIS Fuzzy Statistic	Fuzzy AHP Statistic	Simulation modeling
Geographical location (traffic system, intermodal, hinterland links	Tras. modeling AHP, TOPIS Fuzzy Statistic	Trans. model AHP, TOPIS Fuzzy Statistic	Trans. model AHP, TOPIS Fuzzy Statistic	Trans. mode Fuzzy AHP, TOPSIS Statistic	No
Environment/ weather impacts, management	N/A	N/A	N/A	N/A	Simulation modeling

Despite the wide application of MCDM in various domains and the method allows us to include a wide range of quantitative and qualitative variables to evaluate the port performance However, the disadvantage is that it relies mainly on expert's judgment, and, so not detailed and reliable enough for a long-term study (Nazemzadeh & Vanelslander, 2015). Furthermore, MCDM is generally not too effective in the case of newly projected seaports. This study defers from the literature by introducing the simulation approach, MCDM method and additional practical aspects of port operation, as clarified in the last column of Table 2.

3. Study Area and Proposed Methodology

Recently, demand of cargo imports and exports through existing Cua Lo Port (Fig.2) is increasing remarkably while cargo handling capacity of the existing port is limited. Simultaneously, in coming years, factories in economic zones and industries zones are going to be operated, the demand on fuel import and export will increase quickly. Hence, to cope with the increase of cargo handling demands to increase economic efficiency of the enterprises, promote local economy's development; Nghe An province decided to develop a new Petrol Base at offshore of Cua Lo area to be an internationally standardized petrol port which can receive large oil and gas tankers. The study methodology considered to determine the optimal port location is illustrated in Fig. 3.

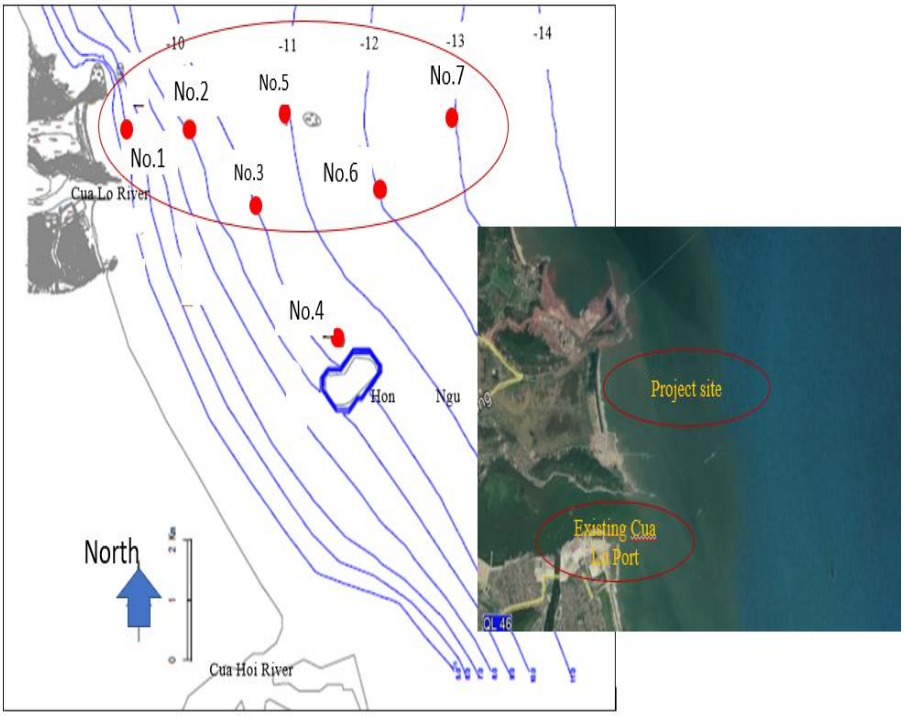


Figure 2. Project site and location alternatives.

A project formulation study (JPC, 2015) had been conducted to investigate the site and to collect data of surrounding projects. As the results, seven location alternatives proposed for the comparison as shown in Fig 3. Natural conditions and investigations at the project site for the seven potential location alternatives were carried out with the scope listed in Fig. 4.

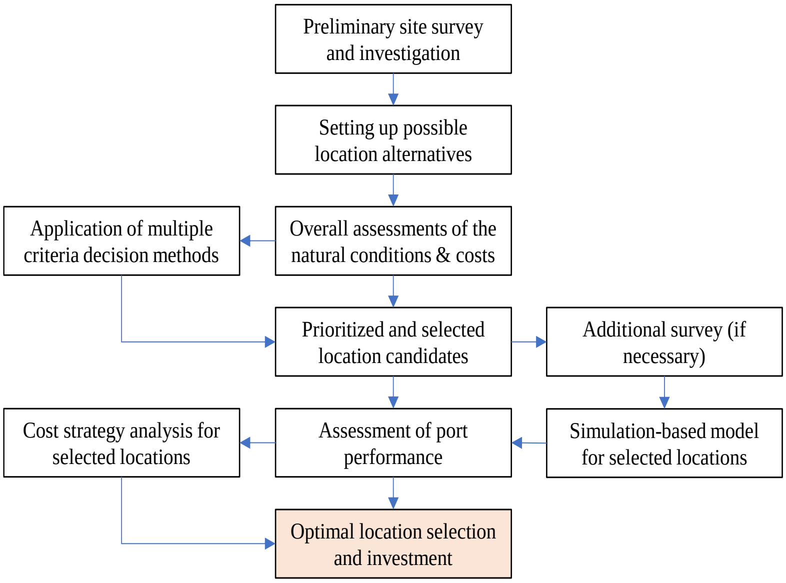


Figure 3. Methodology for proposed framework

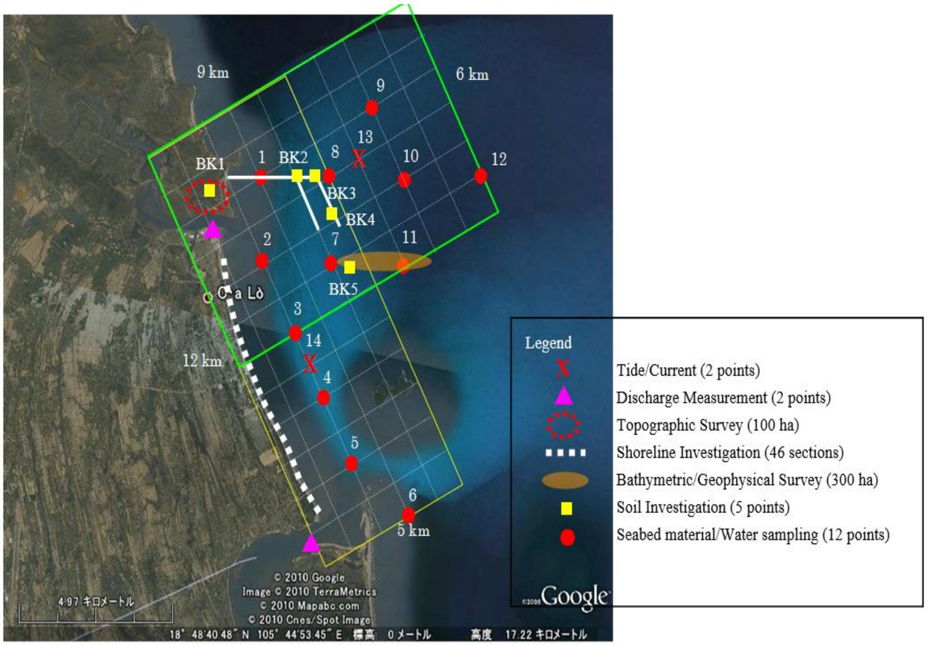


Figure 4. Scope of the surveys

Based on the surveyed results and collected data, the study implemented extensive simulation experiments, including wave propagation simulations, siltation and mud transport simulations, and coastal change simulations. The comparative criteria were created and overall assessment for each location based on the simulation studies and port planning experts from Japan Port Consultants(JPC, 2015), as given in Table 3.

Table 3. Comparison of Locational Alternatives

Criteria	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Wave	Good	Good	Fair	Fair	Bad	Bad	Bad
Current	Good	Bad	Bad	Bad	Fair	Fair	Good
Sediment	Very bad	Bad	Bad	Bad	Fair	Good	Very Good
Subsoil	Good	Fair	Fair	Bad	Fair	Fair	Fair
Present use	Very Good	Very Good	Very Good	Fair	Good	Good	Good
Environment	Very bad	Very bad	Bad	Bad	Fair	Fair	Good
Construction cost	Very Good	Very Good	Good	Fair	Fair	Fair	Bad
Operation cost	Bad	Bad	Bad	Fair	Fair	Fair	Bad

4. Material and Methods

4.1. Rough Analytical Hierarchy Process

This section highlights the steps of rough AHP method (Sambasivam et al., 2020; Vasiljević et al., 2018):

Step 1: Recognize the criteria, sub-criteria, and alternatives that aid in reaching the purposed goal. Afterward, settle the hierarchical structure by the highest level's goal, options in the lower part, and criteria, sub-criteria in the middling section.

Step 2: Consider the pairwise comparison matrix. Gathering of information from experts' opinions with the usage of the values shown in Table 3. The pairwise comparison matrix is:

$$PC_e = \begin{bmatrix} 1 & x_{12}^e & \dots & x_{1n}^e \\ x_{21}^e & 1 & \dots & x_{2n}^e \\ \vdots & \ddots & \vdots & \vdots \\ x_{n1}^e & x_{n2}^e & \dots & 1 \end{bmatrix} \tag{1}$$

where n is the number of criteria, s is the number of expert or decision-makers and $(1 \le e \le s,\ 1 \le r \le n,\ 1 \le c \le n)$ describes the relative importance given by the experts e for the criteria r over criteria c.

Step 3: Determine the highest Eigenvalue λ_{max} of the decision matrix PC_e. Then, identify the Consistency Index (CI) with the use of the formula $CI = (\lambda_{\max} - n)/(n - 1)$. Calculate the Consistency Ratio (CR) of the judgment matrix PC_e with the use of formula, $CR = CI/K$ and Table 4.

Table 4. AHP pairwise comparison table

Importance Level	Comment
1	Equal importance
2	Weak importance
3	Medium importance
4	Medium plus importance
5	High importance
6	High plus importance
7	Very high importance
8	Very, very high importance
9	Extreme high importance

Table 5: Value of Random Integers (K) based on the status of the matrix (Saaty, 1977)

n	1	2	3	4	5	6	7	8	9	10
K	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

The decision matrix is acceptable if in pairwise comparison matrix CR < 0.10. Then, the integrated comparison matrix $\widetilde{CM}$ is formed as,

$$\widetilde{CM} = \begin{bmatrix} 1 & \tilde{x}_{12}^{e} & \dots & \tilde{x}_{1n}^{e} \\ \tilde{x}_{21}^{e} & 1 & \dots & \tilde{x}_{2n}^{e} \\ \vdots & \ddots & \vdots & \vdots \\ \tilde{x}_{n1}^{e} & \tilde{x}_{n2}^{e} & \dots & 1 \end{bmatrix} \tag{2}$$

Step 4: Identify the rough comparison matrix. Change the crisp elements x_{rc}^{e} in the $\widetilde{CM}$ with the use of Equations (1)–(6) into the rough number $V\,(x_{rc}^{e})$,

$$V(x_{rc}^{e}) = [x_{rc}^{eL}, x_{rc}^{eU}] \tag{3}$$

where x_{rc}^{eL} is the lower limit and x_{rc}^{eU} shows the higher limit of $V\,(x_{rc}^{e})$.

The collection of rough numbers with various decision-makers are described by $V\,(x_{rc}^{e})$ as,

$$V(x_{rc}^{e}) = \{[x_{rc}^{1L}, x_{rc}^{1U}], [x_{rc}^{2L}, x_{rc}^{2U}], \dots, [x_{rc}^{sL}, x_{rc}^{sU}]\} \tag{4}$$

It is more merged into the single set by using the average of $V\,(x_{rc}^{e})$ with rough arithmetic formulas,

$$V(x_{rc}) = [x_{rc}^{L}, x_{rc}^{U}] \tag{5}$$

$$x_{rc}^{L} = \frac{x_{rc}^{1L} + x_{rc}^{2L} + \dots + x_{rc}^{sL}}{s} \tag{6}$$

$$x_{rc}^{U} = \frac{x_{rc}^{1U} + x_{rc}^{2U} + \dots + x_{rc}^{sU}}{s} \tag{7}$$

where x_{rc}^{L} and x_{rc}^{U} are the lower and higher limits of $V\,(x_{rc})$, respectively.

Next, the rough comparison matrix *RO* is designed as,

$$RO = \begin{bmatrix} [1,1] & [x_{12}^{L}, x_{12}^{U}] & \cdots & [x_{1m}^{L}, x_{1m}^{U}] \\ [x_{21}^{L}, x_{21}^{U}] & [1,1] & \dots & [x_{2m}^{L}, x_{2m}^{U}] \\ \vdots & \vdots & \ddots & \vdots \\ [x_{m1}^{L}, x_{m1}^{U}] & [x_{m2}^{L}, x_{m2}^{U}] & \cdots & [1,1] \end{bmatrix} \tag{8}$$

Step 5: Determine the rough weight w_f of any criterion.

$$w_f = [\sqrt[n]{\Pi_{c=1}^{n} x_{rc}^{U}} w_f, \sqrt[n]{\Pi_{c=1}^{n} x_{rc}^{U}}] \tag{9}$$

$$w'_f = w_f / \max(w_f^{U}) \tag{10}$$

Above w'_f is the normalized weight of the criteria in the structure of a rough set.

4.2. Rough TOPSIS Method

This part exhibits the steps of rough TOPSIS approach as, (Chang et al., 2019; Sambasivam et al., 2020):

Step 1: Make the decision matrix via organizing the information and data from the decision-makers. The matrix compares the performance of every alternative for different criteria. The judgment matrix (JM) is shown as follows,

$$JM = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} x_{11}^{e} & x_{12}^{e} & \cdots & x_{1n}^{e} \\ x_{21}^{e} & x_{22}^{e} & \cdots & x_{2n}^{e} \\ \vdots & \cdots & \ddots & \vdots \\ x_{m1}^{e} & x_{m2}^{e} & \cdots & x_{mn}^{e} \end{bmatrix} \end{array} \tag{11}$$

where x_{iz}^{e} $(i = 1,2,\dots,m; z = 1,2,\dots,n)$ is the appearance rating of *i*th alternative by the *z*th criteria provided via the *e*th expert and $e = 1,2,\dots,l$.

Step 2: Change the crisp values to the rough values $V(x_{iz}^{e})$ with the use of the equations (3) to (7), and create the rough group decision matrix. The form of rough set values are,

$$V(x_{iz}^{e}) = [x_{iz}^{eL}, x_{iz}^{eU}] \tag{12}$$

where x_{iz}^{eL} is the lower and x_{iz}^{eU} is the higher limits of rough number $V(x_{iz}^{e})$.

Therefore, the merged rough collection progression $V(x_{iz})$ is achieved as follow,

$$V(x_{iz}) = \{[x_{iz}^{1L}, x_{iz}^{1U}], [x_{iz}^{2L}, x_{iz}^{2U}], \dots, [x_{ij}^{eL}, x_{iz}^{eU}]\} \tag{13}$$

With the use of rough computational principles, the average of $V(x_{iz})$is achieved as,

$$\overline{V(x_{ij})} = [x_{iz}^{L}, x_{iz}^{U}] \tag{14}$$

$$x_{iz}^{L} = (x_{iz}^{1L} + x_{iz}^{2L} + \cdots + x_{iz}^{eL})/e \tag{15}$$

$$x_{iz}^{U} = (x_{iz}^{1U} + x_{iz}^{2U} + \cdots + x_{iz}^{eU})/e \tag{16}$$

Next, the structure of the rough group decision matrix is as,

$$RO = \begin{bmatrix} [1,1] & [x_{12}^{L}, x_{12}^{U}] & \cdots & [x_{1m}^{L}, x_{1m}^{U}] \\ [x_{21}^{L}, x_{21}^{U}] & [1,1] & \dots & [x_{2m}^{L}, x_{2m}^{U}] \\ \vdots & \vdots & \ddots & \vdots \\ [x_{m1}^{L}, x_{m1}^{U}] & [x_{m2}^{L}, x_{m2}^{U}] & \cdots & [1,1] \end{bmatrix} \tag{17}$$

Step 3: Compute the normalized rough weighted matrix. The normalization formula is,

$$x_{iz}^{\prime L} = \frac{x_{iz}^{L}}{Max_{i=1}^{m}\{\max[x_{iz}^{L}, x_{iz}^{U}]}, x_{iz}^{\prime U} = \frac{x_{iz}^{U}}{Max_{i=1}^{m}\{\max[x_{iz}^{L}, x_{iz}^{U}]\}} \tag{18}$$

$[x_{iz}^{\prime L}, x_{iz}^{\prime U}]$ is the normalized form of rough set $[x_{iz}^{L}, x_{iz}^{U}]$, and the normalization method as mentioned earlier matches the values in the interval of [0, 1].

Next, the computation of the normalized weighted matrix is as,

$$q_{iz}^{L} = w_{z}^{L} \ * x_{iz}^{\prime L}, i = 1,2, \dots m; z = 1,2, \dots, n. \tag{19}$$

$$q_{iz}^{U} = w_{z}^{U} \ * x_{iz}^{\prime U}, i = 1,2, \dots m; z = 1,2, \dots, n. \tag{20}$$

Where, w_{z}^{L} and w_{z}^{U} describe the weight of criteria in the structure of rough.

Step 4: Determine the Negative Ideal Solution (NIS) and Positive Ideal Solution (PIS) which $q^{+}(z)$ and $q^{-}(z)$ are PIS and NIS of criteria z, respectively. B is related to benefit criteria and C is related to cost criteria.

$$\begin{gathered} q^{+}(z) = \{max_{i=1}^{m}(q_{iz}^{U}), if\ z \in B; min_{i=1}^{m}(q_{iz}^{L}), if\ z \in C\}, \\ q^{-}(z) = \{min_{i=1}^{m}(q_{iz}^{L}), if\ z \in B; max_{i=1}^{m}(q_{iz}^{U}), if\ z \in C\} \end{gathered} \tag{21}$$

Step 5: Determine the n-dimensional Euclidean distance of any criteria from NIS and PIS. d_{i}^{+} is defined as the degree of separation from PIS and d_{i}^{-} is the degree of separation from NIS . They are determined as,

$$d_{i}^{+} = \{\sum_{z \in B}\left(q_{iz}^{L} - q^{+}(z)\right)^{2} + \sum_{z \in C}\left(q_{iz}^{U} - q^{+}(z)\right)^{2}\}^{\frac{1}{2}} \ i = 1,2 \dots, m; z = 1,2, \dots, n. \tag{22}$$

$$d_i^- = \{\sum_{z\in B} \left(q_{iz}^U - q^-(z)\right)^2 + \sum_{z\in C} \left(q_{iz}^L - q^-(z)\right)^2\}^{\frac{1}{2}} \quad i = 1,2 \ldots, m; z = 1,2, \ldots, n. \qquad (23)$$

Step 6: A closeness coefficient (C_i) s estimated to determine the order of ranking of the options.

$$C_i = \frac{d_i^-}{d_i^+ + d_i^-}\ ; i = 1,2, \ldots, m. \qquad (24)$$

The degree of choices is provided based on the decreasing order values of C_i. The alternative nearest to PIS and farthest from NIS will be first priority.

4.3. Application of MCDM methods for the port location ranking

In this study, three experts were selected who have vast experience in this field. The expert's opinions or judgments were used to develop rough AHP-TOPSIS framework. The process of the developed model is discussed below.

4.3.1 Implementation of Rough AHP method

Firstly, eight criteria (i.e., Wave, Current, Sediment, Subsoil, Present use, Environment, Construction cost, and Operation cost) are chosen for the selection of appropriate offshore port location based on the literature review presented in Table 2. Seven alternative locations are considered in this analysis.

In this study, three port planning and port facilities experts from Japan Port Consultants (JPC, 2015) provided their judgment to calculate the weights of the criteria using the pairwise comparison values presented in Table 4. The compiled judgments provided by the three decision-makers are presented in Table 6. After that, the integrated judgment matrix is transformed into rough judgment matrix by using the Equations (3)–(7). Table 6 shows the integrated rough decision matrix.

Table 6. Judgment matrix of the three decision makers to compare the criteria.

Criteria	Wave	Current	Sediment	Subsoil	Present use	Environment	Construction cost	Operation cost
Wave	(1,1,1)	(2,2,2)	(2,1,1)	(3,3,7)	(6,5,4)	(½,1,1)	(1/2,1/2,1)	(1/2,1/2,1)
Current	(1/2,1/2,1/2)	(1,1,1)	(2,1/2,1/2)	(2,3/2,3)	(4,3,2)	(1/3,1/2,1/3)	(1/3,1/3,1/3)	(1/3,1/3,1/3)
Sediment	(1/2,1,1)	(1/2,2,2)	(1,1,1)	(2,4,6)	(3,7,3)	(1/3,1,1/2)	(1/3,1,1/2)	(1/3,1,1/2)
Subsoil	(1/3,1/3,1/7)	(1/2,2/3,1/3)	(1/2,1/4,1/6)	(1,1,1)	(2,2,1/2)	(1/4,1/4,1/8)	(1/4,1/4,1/8)	(1/4,1/4,1/8)
Present use	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1/3,1/7,1/)	(1/2,1/2,2)	(1,1,1)	(1/9,1/7,1/4)	(1/9,1/8,1/4)	(1/9,1/8,1/4)
Environment	(2,1,1)	(3,2,3)	(3,1,2)	(4,4,8)	(9,7, 4)	(1,1,1)	(1,1,1)	(1,1,1)
Construction cost	(2,2,1)	(3,3,3)	(3,1,2)	(4,4,8)	(9,8,4)	(1,1,1)	(1,1,1)	(1,1,1)
Operation cost	(2,2,1)	(3,3,3)	(3,1,2)	(4,4,8)	(9,8,4)	(1,1,1)	(1,1,1)	(1,1,1)

Table 7. Rough judgement matrix to determine the weights of the criteria.

Criteria	Wave	Current	Sediment	Subsoil	Present use	Environment	Construction cost	Operation cost
Wave	(1,1)	(2,2)	(1.11,1.56)	(3.44,5.22)	(4.50,5.50)	(0.72,0.94)	(0.56,0.78)	(0.56,0.78)
Current	(0.50,0.50)	(1,1)	(0.67,1.33)	(1.81,2.56)	(2.50,3.50)	(0.35,0.43)	(0.33,0.33)	(0.33,0.33)
Sediment	(0.72,0.94)	(1.17,1.83)	(1,1)	(3.00,5.00)	(3.44,5.22)	(0.45,0.79)	(0.45,0.79)	(0.45,0.79)
Subsoil	(0.23,0.31)	(0.42,0.58)	(0.23,0.39)	(1,1)	(1.17,1.83)	(0.18,0.24)	(0.18,0.24)	(0.18,0.24)
Present use	(0.19,0.23)	(0.30,0.43)	(0.23,0.31)	(0.67,1.33)	(1,1)	(0.14,0.20)	(0.13,0.20)	(0.13,0.20)
Environment	(1.11,1.56)	(2.44,2.89)	(1.50,2.50)	(4.44,6.22)	(5.39,7.89)	(1,1)	(1,1)	(1,1)
Construction cost	(1.44,1.89)	(3,3)	(1.50,2.50)	(4.44,6.22)	(5.67,8.17)	(1,1)	(1,1)	(1,1)
Operation cost	(1.44,1.89)	(3,3)	(1.50,2.50)	(4.44,6.22)	(5.67,8.17)	(1,1)	(1,1)	(1,1)

The rough numbers of Table 7 are converted into the rough weights of the criteria using Equation (10). Then, the normalization of weights (between 0 to 1) are performed with the help of Equation (11). The weights of the criteria are also determined using the traditional AHP method and it is shown in Table 8. Fig. 5 shows the weights of the criteria collected from the Rough AHP to the traditional AHP method.

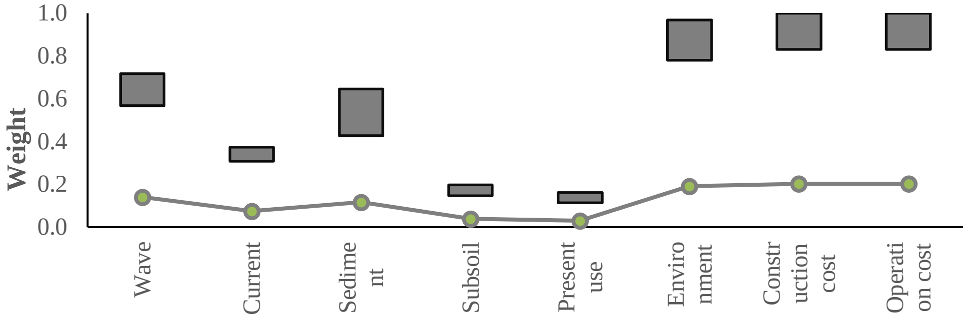


Figure 5: Weights of criteria using rough-AHP and AHP methods.

Table 8: Weights of the criteria using Rough AHP and AHP methods.

Criteria	Rough AHP				AHP
	w_a		w'_a		
	Low Value	High Value	Low Value	High Value	
Wave	1.290	1.635	0.567	0.718	0.142
Current	0.702	0.854	0.308	0.375	0.075
Sediment	0.974	1.472	0.428	0.647	0.118
Subsoil	0.332	0.452	0.146	0.198	0.038
Present use	0.258	0.367	0.113	0.161	0.030
Environment	1.773	2.201	0.779	0.967	0.193
Construction cost	1.891	2.276	0.831	1.000	0.202
Operation cost	1.891	2.276	0.831	1.000	0.202

4.3.2 Implementation of Rough TOPSIS approach

In this stage, the performance of each location alternatives was assessed by the three decision-makers using the qualitative scale and corresponding score values are highlighted in Table 9. The judgment matrix or performance matrix of the seven location alternatives by the three decision-makers are shown in Appendix B1-B3.

Table 9: TOPSIS performance rating scale.

Scale	Score Values
Very bad	1
Bad	2
Fair	3
Good	4
Very good	5

The performance matrices of the three decision-makers are integrated following a similar process of the rough-AHP method and Table B4 indicates the combined performance matrix of the seven location alternatives using the score values presented in Table 10. After that, the aggregated performance matrix was transferred into the rough matrix by using the Equations (3)–(7). Table 8 represents the rough performance matrix of the location alternatives with respect to criteria.

Table 10. Rough Performance matrix of the location alternatives with respect to criteria

Criteria	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Wave	(4,4)	(4,4)	(3,3)	(3,3)	(2,2)	(2,2)	(2,2)
Current	(4,4)	(2,2)	(2,2)	(2,2)	(3,3)	(3,3)	(4,4)
Sediment	(1,1)	(2,2)	(2,2)	(2,2)	(3,3)	(4,4)	(5,5)
Subsoil	(4,4)	(3,3)	(3,3)	(2,2)	(3,3)	(3,3)	(3,3)
Present use	(5,5)	(5,5)	(4.11,4.56)	(3,3)	(3.11,3.56)	(3.44,3.89)	(3.44,3.89)
Environment	(1,1)	(1,1)	(1.44,1.89)	(2,2)	(3,3)	(3,3)	(4,4)
Construction cost	(5,5)	(4.44,4.89)	(4,4)	(3,3)	(3,3)	(3,3)	(1.5,2.5)
Operation cost	(1.11,1.56)	(1.11,1.56)	(2,2)	(3,3)	(3,3)	(3,3)	(2.11,2.56)

In this study, all the criteria are considered cost criteria (lower is better) except subsoil (higher is better) and the normalization was performed by using the Equation (18). Then, the weighted normalized matrix was determined using Equations (19) and (20). Table 11 highlights the rough weighted normalized matrix of the seven location alternatives with respect to the criteria. After that, the PIS and NIS of criteria is determined using the Equation (21) and is shown in Table 12.

Table 11. Rough weighted normalized matrix of the location alternatives

Criteria	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Wave	(0.453,0.574)	(0.453,0.574)	(0.373,0.473)	(0.566,0.718)	(0.318,0.404)	(0.283,0.359)	(0.226,0.287)
Current	(0.246,0.3)	(0.123,0.15)	(0.135,0.164)	(0.205,0.25)	(0.26,0.316)	(0.231,0.281)	(0.246,0.3)
Sediment	(0.085,0.129)	(0.171,0.258)	(0.187,0.283)	(0.285,0.431)	(0.361,0.545)	(0.428,0.646)	(0.428,0.646)
Subsoil	(0.116,0.158)	(0.087,0.119)	(0.096,0.13)	(0.097,0.132)	(0.123,0.167)	(0.109,0.148)	(0.087,0.119)
Present use	(0.113,0.161)	(0.113,0.161)	(0.102,0.161)	(0.113,0.161)	(0.099,0.161)	(0.097,0.156)	(0.078,0.125)
Environment	(0.155,0.193)	(0.155,0.193)	(0.246,0.401)	(0.519,0.644)	(0.657,0.816)	(0.584,0.725)	(0.623,0.773)
Construction cost	(0.83,1)	(0.738,0.977)	(0.729,0.878)	(0.83,1)	(0.701,0.843)	(0.623,0.75)	(0.249,0.5)
Operation cost	(0.184,0.311)	(0.184,0.311)	(0.364,0.439)	(0.83,1)	(0.701,0.843)	(0.623,0.75)	(0.35,0.511)

Table 12. Positive and negative ideal solutions of the criteria

Criteria	Wave	Current	Sediment	Subsoil	Present use	Environment	Construction cost	Operation cost
PIS	0.227	0.123	0.086	0.167	0.078	0.156	0.249	0.185
NIS	0.718	0.317	0.647	0.088	0.161	0.816	1.000	1.000

The distance of each alternative from PIS and NIS was calculated using Equations (22) and (23), respectively and the values are highlighted in Table 13. Finally, the closeness coefficients (CC_i) of the alternatives were determined using the Equation (24) and the rank of the alternatives are also represented in Table 13. Based on the results obtained using the rough AHP-TOPSIS method, the best or ideal location for offshore port allocation is No. 2 because of its highest closeness coefficient (CC_i) value (0.614) followed by location No. 1 ($CC_i = 0.604$). The least preferred location would be No. 4 as it has the minimum CC_i) value (0.269). The ranking of all the location alternatives is in the order of No.2 > No.1 > No.3 > No.7> No.6 > No.5 > No.4.

Table 13. Rank and closeness coefficient (CCi) of the alternatives

Alternatives	*d+*	*d-*	CC_i	Rough-TOPSIS
No. 1	1.073	1.637	0.604	2
No. 2	1.007	1.602	0.614	1
No. 3	0.969	1.373	0.586	3
No. 4	1.706	0.629	0.269	7
No. 5	1.529	0.786	0.339	6
No. 6	1.382	0.924	0.401	5
No. 7	1.136	1.415	0.555	4

4.3.3 Model Comparison

To represent the effectiveness and the validity of the Rough AHP-TOPSIS method, the rank of the alternative locations was determined using AHP, TOPSIS, and crisp AHP-TOPSIS method. Both Table 14 and Fig. 6 indicate differences between the ranking of the alternative locations.

Table 14. Rank of the locations using different methods

Alternatives	AHP	TOPSIS	AHP-TOPSIS	Rough-TOPSIS
No. 1	3	1	1	2
No. 2	5	2	2	1
No. 3	6	3	4	3
No. 4	7	7	7	7
No. 5	4	6	6	6
No. 6	1	5	5	5
No. 7	2	4	3	4

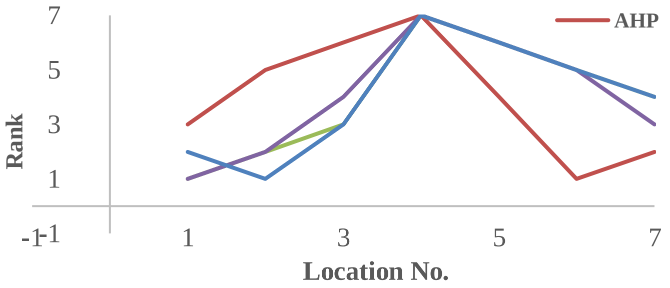


Figure 6. Rank of the locations for different methods

4.4. Simulation-based Assessment

Numerous simulation models with different levels of accuracy and capacity are used for a wide range of applications in the maritime field. Simulation is generally implemented to explore ship maneuvering behavior in micromodels (transit of ship under specified external conditions) or ship traffic in macromodels (within waterway and port systems). The goal of developing traffic simulation models can differ based on specific goals. For example, investigation of traffic behavior (Almaz & Altiok, 2012; Gucma et al., 2016), assessment of port layout and investment (Cho et al., 2022; Nguyen Minh, Sadiq, & Gucma, 2021; Scott et al., 2016; Tang et al., 2017; Wang et al., 2018) and identification of challenges in ship handling and port operation (Cao & Lam, 2019; Cho et al., 2022).

The purpose of the present simulation application is to reveal whether the proposed location alternatives, with its operation rules and environmental conditions, can handle the demand traffic volume and to determine ship waiting time (downtime) and ship times at the port (turnaround times). The environmental conditions for which a ship's operation is considered safe or unsafe are referred to as port safety policy. The farther facilities located from the shoreline, the lesser dredging required for initial and maintenance constructions of the water areas, and environmental impacts are therefore minimized, but construction and operation costs for the facilities and transportation means might be increased, and harder weather attacks to the port activities. The simulation results of port performance can provide a merit information considered as the basis for calculation of running cost during the project life. Ranking the port location alternatives based on the cost-benefit analysis model (CBA) would be therefore done. The procedures of the simulation application for this purpose are described in the following sections.

4.4.1 Simulation model

In an earlier study, Nguyen Minh et al. (2021) performed a discrete event process-interaction-based simulation model to handle shipping activities at ports. Some key features of that model are discussed as follows:

1. Based on the historical information, ship arrival at the port is randomly generated by a given probability distribution function.
2. Climate factors include the wave (period, height, and wave direction), wind (speed and direction), and current (direction and speed) are generated randomly based on historical data.
3. Hourly tidal water levels of at least one year are considered during the simulation period.
4. The model considered all port processes and facilities including approach channel, anchor areas, berths, turning basin, and in addition to safety criteria.
5. The ships are categorized based on the size and type, regulated berthing at four groups of terminals like container, bulk, general cargo, and other terminals.
6. According to the performance-based approach prosed by Ohtsu et al. (2006), margins of ship motions in a confined waterway under external impacts are considered.
7. According to the port information guideline, the model calculated a ship speed as a constant variable through the passage considering the external impact.
8. The simulated results are highlighted in statistical and probabilistic distributed forms

considering all the port activities and processes.

9. Lastly, based on the simulated results, cost-based strategy analysis is performed to optimize port investment.

4.4.2 Simulation experiments

At the initial stage, one berth for Gasolin ships up to 70,000 DWT and one container berth for fuel/diesel ships up to 30,000 DWT are considered. The approach channel and access trestle have different lengths depending on the locations of the berthing facility, as presented in Table 15 and Fig. 7. Based on the historical information collected from the Vietnamese Ports, a wide range of the designed ship fleet with their dimensions was considered in the simulation study (Table 16). A total of ten ship types were grouped into Gasolin (LOT_No.) and diesel/fuel (SOT_No.) ships. The percentage (%) arrival rate of ships were estimated based on the historical data with minor adjustments. According to the designed handling rate for normal working conditions, the average service times (ST) for cargo handling were estimated.

Table 15. Data of port location alternatives for the simulation

Items	Details	Locations					
		No.1	No.2	No.3	No.5	No.6	No.7
Channel	Length (m)	10,000	9,000	7,200	5,300	4,000	500
	Width (m)	200	200	200	200	200	200
	Depth (m)	13.0	13.0	13.0	13.0	13.0	13.0
Trestle	Length (m)	500	1,500	3,800	5,000	7,000	8,500
	Width (m)	10	10	10	10	10	10

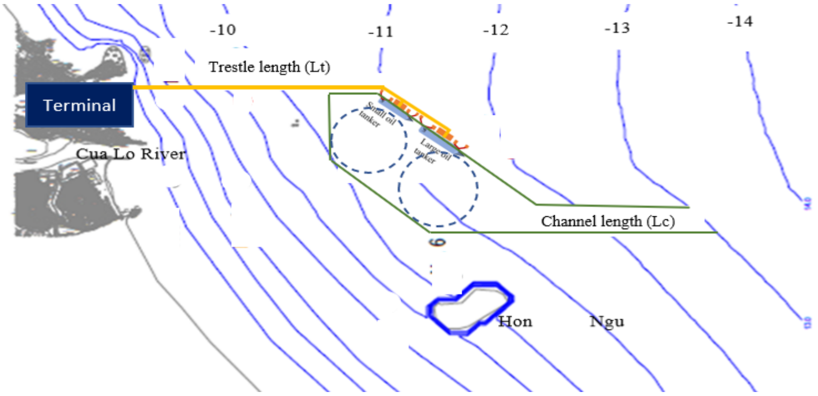


Figure 7. Scheme of port layout

Table 16. Ship data

Ship index		DWT	Lpp	B	Draft	Arrival rate (%)	Cargo type	Mean ST (hours/ship)
1	LOT_1	70,000	228	38.1	12.5	20%	Gasolin	38.9
2	LOT_2	50,000	209	34.3	11.5	30%	Gasolin	29.4
3	LOT_3	30,000	184	29.1	10.4	25%	Gasolin	20.0
4	LOT_4	20,000	166	25.6	9.3	25%	Gasolin	16.7
5	SOT_1	30,000	184	29.1	10.4	15%	Diesel	16.7
6	SOT_2	20,000	166	25.6	9.3	20%	Diesel	13.3
7	SOT_3	15,000	154	23.4	8.6	30%	Diesel	12.5
8	SOT_4	10,000	139	20.6	7.6	25%	Jet fuel	10.0
9	SOT_5	5,000	100	16.7	6.4	10%	Jet fuel	6.30

4.4.3 Environmental conditions

Wind conditions considered unchanged for all alternatives are, therefore, disregarded. Data of waves at offshore Cua Lo area has been collected as the tables of frequencies distinguished based on the classes of different values and directions. Near shore waves and currents at the proposed port locations have been estimated from the offshore waves using wave transmission model (JPC, 2015). The simulated current data has been verified based on the observed results with expert' assessment. The relationships of wave and current data for different port locations are defined as presented in Table 17. Based on that, the wave and current data for are then generated using stochastically distributed functions and inverse transformation methods (Wendy and & Angel 2002). By checking with the safety operation policies (Table 18), we can estimate times of port downtime and ship times at port for each alternative due to the adverse weathers. One year of hourly measured tidal levels were used in the simulation to handle the effect of water tidal variation on the navigational depth.

Table 17. Relationship of waves and current at different port locations

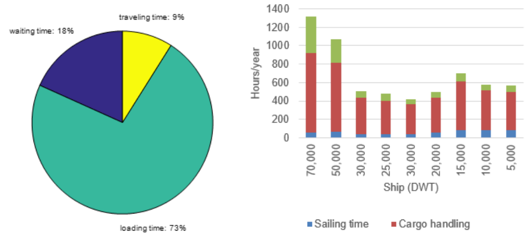
Items	Details	Locations					
		No.1	No.2	No.3	No.5	No.6	No.7
Wave	Height H_s (m)	$H_{s1}=0.4 H_{s7}$	$H_{s2}=0.4H_{s7}$	$H_{s3}=0.7 H_{s7}$	$H_{s5}= H_{s7}$	$H_{s6}= H_{s7}$	H_{s7}
	Period (sec)	Same					
Current	Speed, Vc (m/s)	$V_1=V_7$	$V_2=0.4 V_7$	$V_3=0.4V_7$	$V_5=0.3V_7$	$V_6=0.3V_7$	V_7
	Direction	North					

Table 18. Safety operation policy

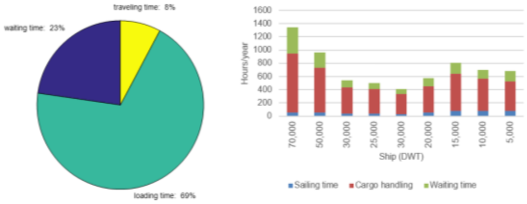
Place	Description	$V_{current}$ (m/s)	Hs (m)
Turning areas	With tugboats	≤0.1 m/s	<1.7 m
Vessel berthing	Longitudinal to berth	≤1.0 m/s	≤2.0 m
	Transverse to berth	≤0.1 m/s	≤1.5 m
Operations	Longitudinal to berth		
	<30,000 DWT	≤1.5 m/s	≤1.5 m
	>=30,000 DWT	≤1.5 m/s	≤2.0 m
	Transverse to berth		
	<30,000 DWT	≤0.7 m/s	≤1.0 m
	>=30,000 DWT	≤0.7 m/s	≤1.2 m

4.4.4 Simulation results

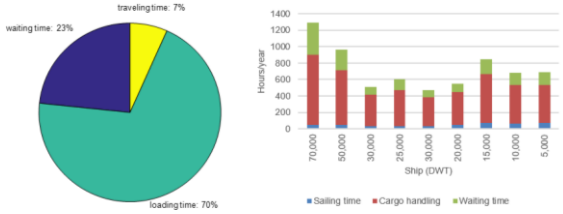
The simulation execution was conducted with at least 30 iterations to determine different port performance indicators. Various port performance indictors like cause of delay or waiting times per location, berth occupancy, turnaround time for each ship, number of tugboats used, number of ships in the queue, cargo throughput for each ship and berth are determined from the simulation. Fig. 8 shows some of the main outputs. In these scenarios, we targeted to the same forecasted number of ship arrivals. Figure 9 presents the simulated results of ship times at port.



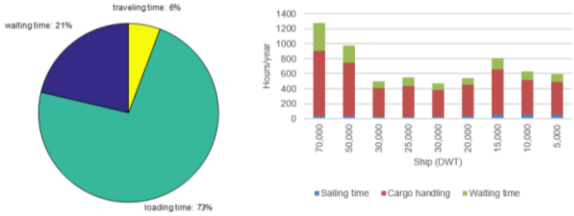
Location No.1



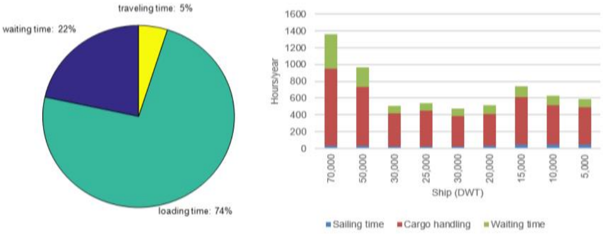
Location No.2



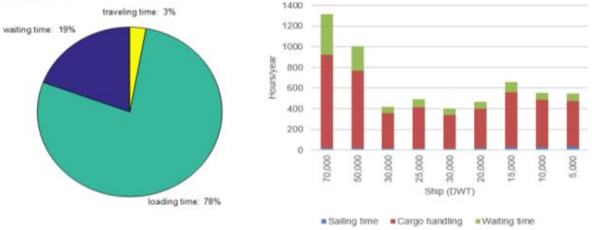
Location No.3



Location No.5



Location No.6



Location No.7

Figure 8. Simulated results of ship performance

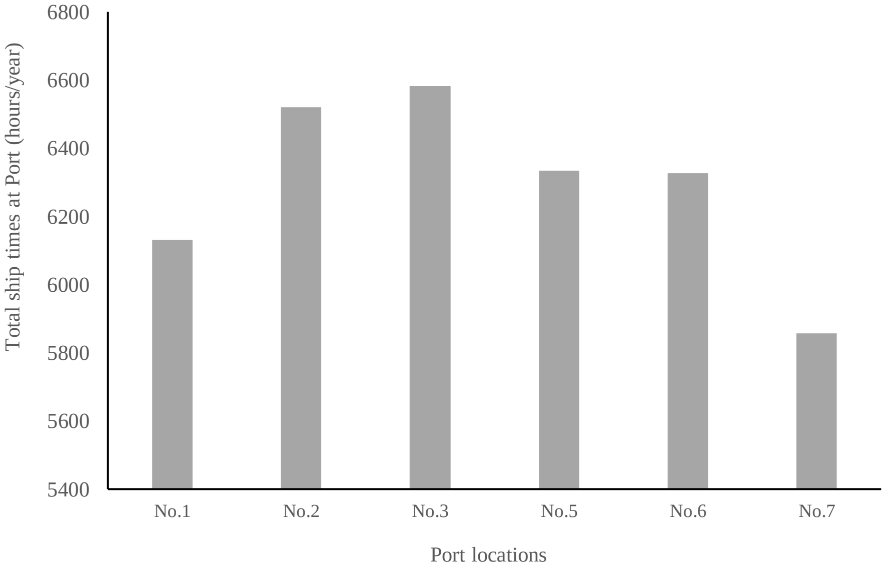


Figure 9. Simulated results of ship times at Port

4.5. Cost-Benefit Analysis (CBA)

The cost-benefit analysis is performed to assess the cash flow through the project life. In this study, Net Present Value (NPV) indicator is calculated to represent the net present value of the complete future project cash flow. The general formula if NPV is:

$$NPV = \sum_{t=0}^{T} \frac{R_t}{\left(1+r_t\right)^t} = \sum_{t=0}^{T} \frac{\left(B_t - C_t\right)}{\left(1+r_t\right)^t} \tag{25}$$

Where,

T : project lifetime (30 – 40 years)
B_t : annual income of the port,
r_t : discount rate,
t : year number t of the project
C_t : initial cost and total operation costs at year number of t

As cargo throughput is targetted seven million tons for all alternatives, the annual port income can be is cosnidred same for all alternatives. For this, Eq. (25) can be revised as follow:

$$\boldsymbol{NPV(C_t) = \sum_{t=0}^{T} \frac{C_t}{(1+r_t)^t}} \tag{26}$$

Preliminary construction cost and estimations of operating cost were made in for comparing items based on construction quantities (Table 19) and the unit costs of the basic design (JPC 2015), as shown in Table 20 and Table 21. Table 22 summarized the comparison of the expert’s assessment with cost estimates.

Table 19. Construction quantities

No.	Items	Unit	Location alternatives					
			No.1	No.2	No.3	No.5	No.6	No.7
1	Initial dredging	m3	8,280,000	5,940,000	3,132,000	801,000	189,000	0
2	Berths	No.	2	2	2	2	2	2
2.a	Large tanker	No.	1	1	1	1	1	1
2.b	Small tanker	No.	1	1	1	1	1	1
3	Trestle and pipeline	m	500	1,500	3,800	5,000	7,000	8,500

Table 20. Construction costs (Unit: 1000 USD)

No.	Items	Location alternatives					
		No.1	No.2	No.3	No.5	No.6	No.7
1	Initial dredging	57,960,000	41,580,000	21,924,000	5,607,000	1,323,000	0
2	Berths	13,700,000	14,385,000	20,550,000	28,050,750	40,072,500	42,076,125
2.a	Large tanker	8,000,000	8,400,000	12,000,000	16,380,000	23,400,000	24,570,000
2.b	Small tanker	5,700,000	5,985,000	8,550,000	11,670,750	16,672,500	17,506,125
3	Trestle and pipe line	5,000,000	18,000,000	45,600,000	60,000,000	84,000,000	122,400,000

Table 21. Construction costs (Unit: 1000 USD)

No.	Items	Unit	Location alternatives					
			No.1	No.2	No.3	No.5	No.6	No.7
1	Annual dredging	USD	17,388,000	12,474,000	6,577,200	961,200	170,100	0
1a	Rate of sediment	%	0.35	0.35	0.35	0.20	0.15	0.00
1b	Dredging volume	m3	2,898,000	2,079,000	1,096,200	160,200	28,350	0
2	Depreciation		1,122,000	1,943,100	3,969,000	5,283,045	7,444,350	9,868,568
3	Ship time cost		7,358,540	7,825,027	7,898,006	7,600,628	7,591,422	7,027,530
4	Total		25,868,540	22,342,127	18,774,206	14,294,873	15,855,872	18,036,098

Table 22. Comparison of the expert's assessment with cost estimates

Criteria	Methods	Location alternatives					
		No.1	No.2	No.3	No.5	No.6	No.7
Environment	MCDM	Very bad	Very bad	Bad	Fair	Fair	Good
	Cost-based	5,000,000	5,000,000	3,000,000	1,000,000	1,000,000	0
Construction cost	MCDM	Very Good	Very Good	Good	Fair	Fair	Bad
	Cost-based	76,660,000	73,965,000	88,074,000	93,657,750	125,395,500	164,476,125
Operation cost	MCDM	Bad	Bad	Bad	Fair	Fair	Bad
	Cost-based	25,868,540	22,342,127	18,774,206	14,294,873	15,855,872	18,036,098

NPVs presented in Fig. 10 are calculated with a 40 years project lifetime and 6% discount rate. The results for ranking of port location alternatives based on different methods are summarized in Fig. 11, in which ranking results of MCDM method are calculated by averaging on the ranks of all methods given in Table 12.

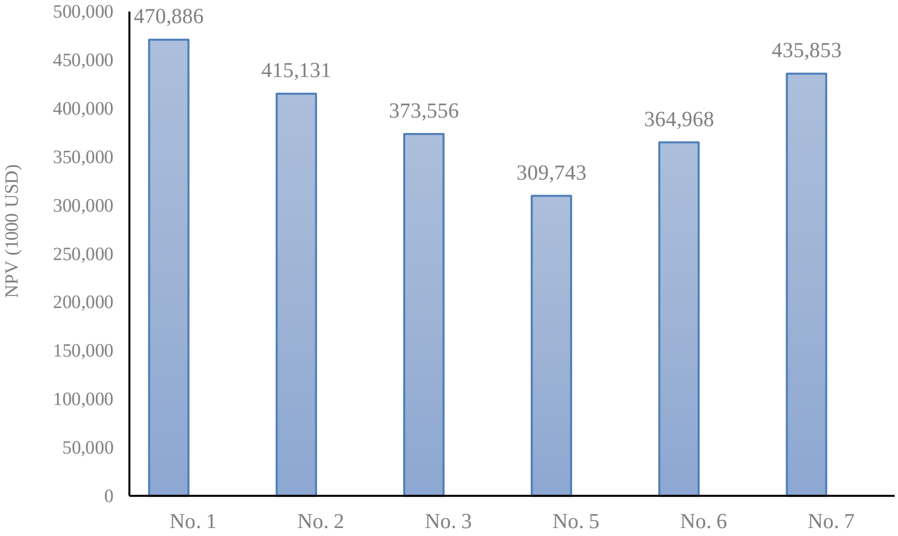


Figure 10. NPV results

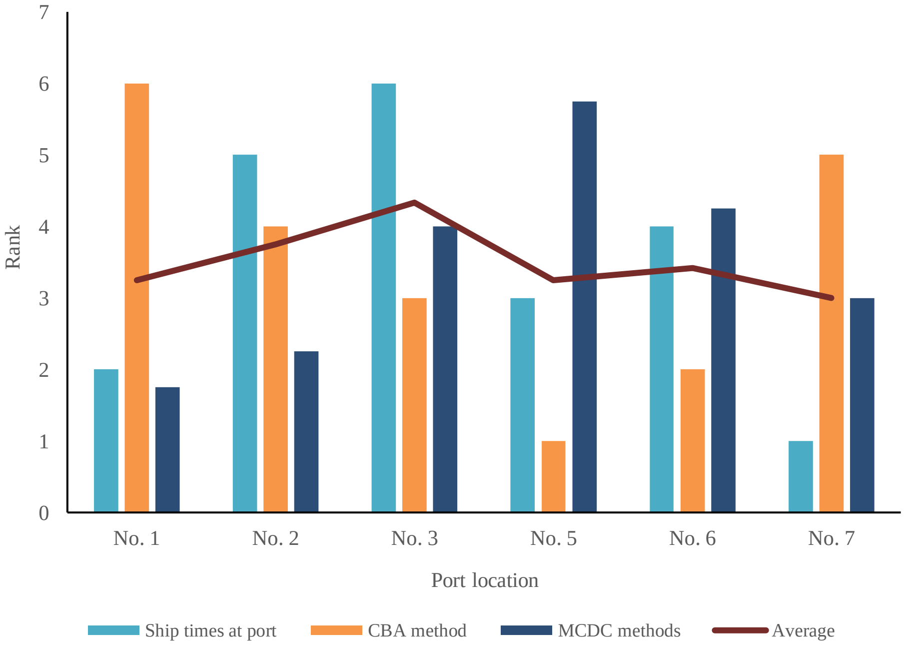


Figure 11. Final ranking results

5. Discussions

This section discussed the results of the proposed methodology. Fig. 5 highlighted the comparison of the weights of the criteria determined using traditional AHP method and Rough AHP method. In the rough AHP method, decision-makers' uncertainties could be known, which includes the values of decision-makers in the mode of higher and lower ranges. In this figure, experts' spread of judgment is shown in a bar-style for the rough AHP method instead of a line with the crisp AHP process. If the length of the bar is high, the uncertainties of decisions by the decision-makers would be more. Also, if the length of the spread is low, the correctness of the choices would be higher. Fig. 5 indicates that the decision-makers are in higher consensus for the subsoil and present use, and current criteria while more uncertain for the sediment, environment, construction cost, operation cost, and wave. Although multiple decision-makers were considered in this study, the weights of the criteria using AHP is shown in the appearance of lines. The conventional AHP method uses the uses the mean value of decision-makers and does not consider the uncertainties and confusion of the judgment values.

It can be seen from Fig. 6 that the rank of the locations using the AHP method varies significantly from the other three methods. The variance was due to inefficiencies within the AHP method, as it cannot differentiate between the benefit and cost criteria during the evaluation and only represent the relative importance of one element over others. In this study, subsoil is considered the beneficial criteria while all the other seven criteria are considered as the cost criteria. For this, the rank of the other methods is more appropriate than the AHP method.

Both Table 12 and Fig. 6 highlight that the No.1 and No.2 are the top two ranked locations using TOPSIS, crisp AHP-TOPSIS, and rough AHP-TOPSIS methods. Fig. 6 also shows that the location No. 4 is the least preferred alternative based on all four methods. The ranking of the rough AHP-TOPSIS and TOPSIS method is almost similar except for the location No.1 and location No. 2. On the other hand, the ranking of the locations No.4, No.5, and No.6 are same for TOPSIS, crisp AHP-TOPSIS, and rough AHP-TOPSIS methods. Based on the above comparison, it can be said that No.2 and No.1 are the most appropriate locations for the offshore port allocation whereas No.4 is the least preferred location as indicated the same results by all methods.

Based on our experiences and knowledge in planning of offshore port development, wind and wave conditions and atmospheres surrounding small islands are normally extremely complicated and sometime unpredictable. Therefore, the option for port development at or near small islands (No.4) is very often denied, as the same result of the above assessment. So, to mitigate the simulation burden, the No.4 location has been eliminated.

Some important and critical findings from the simulated results is discussed follows:

1. According to the expert' assessment in the MCDC method, the impacts of wave and current conditions on the port operation for different port locations are assessed varying from “Bad” to “Good”. However, the impacts of these two combined factors are slightly different as revealed in simulated results of the ship waiting time.
2. Because of the shortest channel length (i.e. longest trestle), the travelling

(sailing) time of ships on the channel for location No.7 is smallest and it is increasing with increasement of the channel length. The cargo handling times are almost unchanged and converted for all port locations.

3. The total ship time for location No.7 is smallest, whereas the highest results found at locations No. 3 and No.2, as shown in Fig. 9. It can be found that the impact of currents on the port operation is much higher than that of waves. This gap of the environmental impact is very hardly recognized based on the expert's experience in the MCDC model.
4. The tide effect has a significant impact on the port operation and more than that of the wave and current, as revealed in the simulated results of waiting times. This effect, however, has been usually omitted in the literature of MCDC method.
5. In view of the most attractive port for ship owner's choice, location No.7 is considered as the first rank.

It can be seen in Table 22 that the expert's assessment reflects relatively well the intendancy of the estimated cost levels for the comparison criteria, respectively. However, the weightings of assessment criteria are somehow not balanced with the increment of the corresponding cost items. NPVs of the seven location (Fig. 10) can be explained that the initial construction cost for nearshore location alternatives is cheaper. However, their NPVs are still higher than those of the other locations because the huge cost spends for maintenance dredging works. Whereas, location No.7 has a lowest ship time cost, but it is the most expensive location is required for initial construction, making its NPV be second top. Location No. 5 achieved a best balance between the construction and operation costs, and therefore, resulted in the lowest NPV. Location No.5 is assessed as the first rank in term of the CBA criterion.

6. Conclusions

Port construction site selection is crucial process and challenging task. This paper develops a new framework to assist port and marine investors in finding the optimum port planning locations in terms of technical and economic viewpoints. The framework includes multicriteria decision-making methods (MCDM) along with experts' judgment and applying a simulation-based model for the facility performance assessment. The MCDM method is useful for evaluating and ranking the priority order for selecting construction sites. However, this method is still mainly based on expert experience, especially since it is not possible to accurately assess the operation of the port in the long term, so it cannot be reliable enough. Simulation method can overcome this drawback, but this method requires relatively large and expensive initial survey data. Therefore, a combination of these two options may be the best choice to reduce survey cots, eliminate the worst alternatives and increase reliability of the choice.

The case study of Cua Lo Port showed that location No.1 is the best according to the evaluation results of the MCDM method. However, if considering the cost of the port operation in the long term, location 5 is the optimal option, as shown by the simulation results. Interestingly, the choice of port location should consider the length of time the ship stays at the port. The shorter the ship's stay at the port, the more attractive it is for the ship to arrive at the port and be chosen by the shipowner. It is also an essential factor but not fully considered in the previous studies.

However, this study focuses mainly on the port activities in wet infrastructure area. Transport vehicles in the terminal and geographical location, as mentioned in Table 2, are not included in the study. This study was performed by considering the inputs of three experts. The accuracy of the proposed framework can be further enhanced considering the inputs of multiple stakeholders in future. In future, the performance of the developed simulation model can be further improved by incorporating additional port operation factors. Future study should target on developing a sophisticated model by considering different port performance factors. The results of the rough AHP-TOPSIS model can be further compared with different MCDM models like fuzzy DEMATEL or rough DEMATEL. These methods can consider the interrelationships between different factors and may provide better insights for the significance of factors and the performance ratings of location alternatives.

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APPENDIX A

Rough Set Theory

The rough set theory provides the importance fundamentally in the artificial intelligence area (Skowron & Dutta, 2018). The application offered a general idea that left a way for employment in different applications for decision making (Chang et al., 2019; Zhang, Xie, & Wang, 2016). The decision-makers are employed to assess the criteria for a particular problem and can prioritize them with the use of the given scale values. It is impossible that all the decision-makers be masters in every area. Some of them may be experienced in one field, and some may be in a different area. Therefore, the judgment would be uncertain if an inexperienced decision-maker makes a decision in a particular area. To find and remove the uncertainties, the rough set approach presents a notable performance, and by removing the vagueness of the experts' idea, it will give the most suitable decision. Seldom, the rough set method can be employed when there are sets distinguished by a minimal mass of data (Pawlak & Skowron, 2007; Vasiljević et al., 2018). The rough set could work great with a small number of data problems and withdraw uncertainty to make the most desirable decision (Sambasivam et al., 2020). The advantages of the rough set theory, which are its usefulness for discovering the hidden patterns in data, estimating the weight of data, and decreasing the primary data, are described in Song et al. (2014).

The pair of precise theories based on the lower and higher estimate is employed to deal with the uncertain issue (Pawlak, 1982). Let U be the world, including all the objects; consider LO as a lower estimate. States that the collection of whole objects can surely be specified in LO. The higher estimate collection of LO consists of components that can undoubtedly relate to LO or not. The boundary region of LO in U of the components in it which cannot be either brought in nor can be brought out as a part of the goal set (Song et al., 2014).

Think, there are e types of experts' idea, $H = \{h_1, h_2, \ldots, h_e\}$, which $h_1 < h_2 < \cdots < h_e$, and O is an arbitrary object of U, next, the higher and lower evaluations of h_i and the boundary region are estimated with,

Lower estimate:

$$\underline{Apr}(h_i) = \cup \{O \in U \mid H(O) \leq h_i\} \tag{1}$$

Higher estimate:

$$\overline{Apr}(h_i) = \cup \{O \in U \mid H(O) \geq h_i\} \tag{2}$$

Boundary region:

$$\begin{aligned} BR(h_i) &= \cup \{ O \in U \mid H(O) \neq h_i \} \\ &= \{ O \in U \mid H(O) > h_i \} \cup \{ O \in U \mid H(O) < h_i \} \end{aligned} \tag{3}$$

Consequently, the class h_i is described in the structure of a rough number, which includes the lower limit $\underline{Lim}(h_i)$ and higher limit $\overline{Lim}(h_i)$ and are calculated as,

$$\underline{Lim}(h_i) = \frac{1}{N_L} \sum H(O) \mid O \in \underline{Apr}(h_i) \tag{4}$$

$$\overline{Lim}(h_i) = \frac{1}{N_U} \sum H(O) \mid O \in \overline{Apr}(h_i) \tag{5}$$

where N_L describes the number of objects which are included for lower evaluation of h_i, and N_U shows the number of objects included for the higher evaluation of h_i.

The personal human judgments can be shown in expressions of rough interval structure based on lower limit $\underline{Lim}(h_i)$ and higher limit $\overline{Lim}(h_i)$.

Rough number:

$$RN(h_i) = [\underline{Lim}(h_i), \overline{Lim}(h_i)] \tag{6}$$

By determining the interval of the boundary region, the level of accuracy of decisions by decision-makers can be examined. The higher level of accuracy happens when the interval of a rough number is smaller.

The interval of boundary region:

$$IBR(h_i) = \overline{Lim}(h_i) - \underline{Lim}(h_i) \tag{7}$$

The arithmetic operations for rough numbers are done as follows,

Addition of rough numbers V_a and V_b,

$$V_a + V_b = \left(\underline{Lim}_a, \overline{Lim}_a\right) + \left(\underline{Lim}_b, \overline{Lim}_b\right) = \left(\underline{Lim}_a + \underline{Lim}_b, \overline{Lim}_a + \overline{Lim}_b\right) \tag{8}$$

Subtraction of rough numbers V_a and V_b,

$$V_a - V_b = \left(\underline{Lim}_a, \overline{Lim}_a\right) - \left(\underline{Lim}_b, \overline{Lim}_b\right) = \left(\underline{Lim}_a - \overline{Lim}_b, \overline{Lim}_a - \underline{Lim}_b\right) \tag{9}$$

Multiplication of rough numbers V_a and V_b,

$$V_a \times V_b = \left(\underline{Lim}_a, \overline{Lim}_a\right) \times \left(\underline{Lim}_b, \overline{Lim}_b\right) = \left(\underline{Lim}_a \times \underline{Lim}_b, \overline{Lim}_a \times \overline{Lim}_b\right) \tag{10}$$

Division of rough numbers V_a and V_b,

$$V_a \div V_b = \left(\underline{Lim}_a, \overline{Lim}_a\right) \div \left(\underline{Lim}_b, \overline{Lim}_b\right) = \left(\underline{Lim}_a \div \overline{Lim}_b, \overline{Lim}_a \div \underline{Lim}_b\right) \tag{11}$$

Scalar multiplication of rough number V_a with non-zero constant p,

$$\mathrm{p} \times V_a = [\mathrm{p} \times \underline{Lim}_a, \mathrm{p} \times \overline{Lim}_a] \tag{12}$$

APPENDIX B

Table B1: Performance of the alternatives by Decision Maker 1

Criteria	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Wave	Good	Good	Fair	Fair	Bad	Bad	Bad
Current	Good	Bad	Bad	Bad	Fair	Fair	Good
Sediment	Very bad	Bad	Bad	Bad	Fair	Good	Very Good
Subsoil	Good	Fair	Fair	Bad	Fair	Fair	Fair
Present use	Very Good	Very Good	Very Good	Fair	Good	Good	Good
Environment	Very bad	Very bad	Bad	Bad	Fair	Fair	Good
Construction cost	Very Good	Very Good	Good	Fair	Fair	Fair	Bad
Operation cost	Bad	Bad	Bad	Fair	Fair	Fair	Bad

Table B2: Performance of the alternatives by Decision Maker 2

Criteria	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Wave	Good	Good	Fair	Fair	Bad	Bad	Bad
Current	Good	Bad	Bad	Bad	Fair	Fair	Good
Sediment	Very bad	Bad	Bad	Bad	Fair	Good	Very Good
Subsoil	Good	Fair	Fair	Bad	Fair	Fair	Fair
Present use	Very Good	Very Good	Good	Fair	Fair	Good	Good
Environment	Very bad	Very bad	Very bad	Bad	Fair	Fair	Good
Construction cost	Very Good	Very Good	Good	Fair	Fair	Fair	Very bad
Operation cost	Very bad	Very bad	Bad	Fair	Fair	Fair	Bad

Table B3: Performance of the alternatives by Decision Maker 3

Criteria	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Wave	Good	Good	Fair	Fair	Bad	Bad	Bad
Current	Good	Bad	Bad	Bad	Fair	Fair	Good
Sediment	Very bad	Bad	Bad	Bad	Fair	Good	Very Good
Subsoil	Good	Fair	Fair	Bad	Fair	Fair	Fair
Present use	Very Good	Very Good	Good	Fair	Fair	Fair	Fair
Environment	Very bad	Very bad	Bad	Bad	Fair	Fair	Good
Construction cost	Very Good	Good	Good	Fair	Fair	Fair	Fair
Operation cost	Very bad	Very bad	Bad	Fair	Fair	Fair	Fair

Table B4: Performance matrix of the location alternatives of the three decision makers

Criteria	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Wave	(4,4,4)	(4,4,4)	(3,3,3)	(3,3,3)	(2,2,2)	(2,2,2)	(2,2,2)
Current	(4,4,4)	(2,2,2)	(2,2,2)	(2,2,2)	(3,3,3)	(3,3,3)	(4,4,4)
Sediment	(1,1,1)	(2,2,2)	(2,2,2)	(2,2,2)	(3,3,3)	(4,4,4)	(5,5,5)
Subsoil	(4,4,4)	(3,3,3)	(3,3,3)	(2,2,2)	(3,3,3)	(3,3,3)	(3,3,3)
Present use	(5,5,5)	(5,5,5)	(5,4,4)	(3,3,3)	(4,3,3)	(4,4,3)	(4,4,3)
Environment	(1,1,1)	(1,1,1)	(2,1,2)	(2,2,2)	(3,3,3)	(3,3,3)	(4,4,4)
Construction cost	(5,5,5)	(5,5,4)	(4,4,4)	(3,3,3)	(3,3,3)	(3,3,3)	(2,1,3)
Operation cost	(2,1,1)	(2,1,1)	(2,2,2)	(3,3,3)	(3,3,3)	(3,3,3)	(2,2,3)