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Assessment of Barrier and Selection of Strategies for Loading and Unloading Operations at Ports using Fuzzy BWM-MABAC

Nadhea Aurelie Salsabila[1]*, Dana Marsetiya Utama[1],
[1)] Faculty of Engineering, Industrial Engineering Department, Muhammadiyah University of Malang
Jl. Raya Tlogomas No. 246, Malang 65144, Indonesia
Email: nadheaaureliesalsabila@gmail.com*, dana@umm.ac.id
*Corresponding author

Abstract: This study developed an integrated Fuzzy Multi-Criteria Decision Making (MCDM) framework to assess obstacles and prioritize improvement strategies for loading and unloading operations at ports. The Fuzzy Best Worst Method (F-BWM) was applied to obtain consistent criterion weights, while Fuzzy MABAC was used to rank six strategic alternatives. Twenty-five operational sub-criteria, adapted and validated by experts, were used to reflect the port context. Results show that modernizing equipment combined with preventive maintenance is the strongest strategy across various sensitivity scenarios. This study contributes to the field by extending the application of hybrid MCDM to the port sector and by demonstrating how integrated methods enhance the weighting and ranking processes. From a managerial perspective, these findings provide structured decision support for port authorities to allocate resources effectively, prioritize technology-based interventions, and plan for long-term improvements in human resources and infrastructure.

Keywords: Fuzzy BWM, Fuzzy MABAC, Port Optimization, MCDM.

Introduction

Loading and unloading are vital activities in a port, as they determine the speed of turnover of goods and ships [1]. The bottleneck of the loading and unloading process is a key indicator of port performance [2, 3]. Inefficiencies in this process can lead to congestion, delays in the distribution of goods, increased operational costs, and disruptions in the global supply chain [4]. Where the speed and accuracy of loading and unloading are key indicators of service user satisfaction [5]. Port operational constraints and logistical inefficiencies can hamper the flow of goods and economic competitiveness, making port performance evaluation and strategic logistics planning equally important [1, 6, 7]. Efforts to enhance the effectiveness of loading and unloading should consider aspects of efficiency, safety, and port infrastructure capacity.

Analysis of loading and unloading effectiveness is necessary to identify factors that hinder port operational performance and to inform design improvement strategies [8]. The effectiveness of loading and unloading at ports is a strategic issue that requires systematic management [9, 10]. In the context of maritime supply chains, it emphasizes the need for resilient strategies to anticipate disruptions that can occur due to inefficiencies at critical points [11]. In line with this, port sustainability is also evaluated through composite indices that integrate social, economic, and environmental dimensions [12, 13]. Underscores that improving port performance requires not only operational management but also resilient facility design. The use of integrated models has been shown to improve the sustainability of vessel traffic management and reduce waiting times [14], while predictive analysis supports more efficient resource allocation [15]. Without effectiveness evaluation, stevedoring activities tend to create inefficiencies that impact the environment and overall port performance [16].

Several studies have highlighted the importance of the assessment aspect of a multi-criteria-based approach in identifying factors that influence Port effectiveness [17, 18]. The fuzzy multi-criteria decision-making approach can be used to identify and evaluate the factors causing these obstacles more comprehensively [19]. Assessing container port service quality with fuzzy AHP [5], PCA-TOPSIS to rank container terminals based on efficiency [6]. Combining fuzzy methods in evaluating port supply chain management performance and strategies in a sustainable manner [20, 21], and in addition, integrating various fuzzy approaches in service assessment and smart port systems [9, 22, 23]. Through the integration of these approaches, it is possible to comprehensively study the effectiveness of loading and unloading at ports, taking into account technical, managerial, and systemic risk aspects [24]. With few pairwise comparisons, the Best-Worst Method (BWM) is effective in producing stable and consistent weights [25]. In particular, the extended *Multi-Attributive Border Approximation Area Comparison* (MABAC) method has proven effective in handling heterogeneous information and decision-making complexity [26-28].

To the best of our knowledge, an integrated Fuzzy BWM-MABAC MCDM framework specifically designed for bottleneck assessment and formulating efficient strategies for loading and unloading processes in ports is currently lacking. Most studies focus on operational efficiency or environmental sustainability using different MCDM methods; it is rare to directly study an integrated approach that addresses both aspects in a structured decision-making model. Fuzzy BWM has been proven effective in producing consistent criterion weights with a relatively small number of comparisons [21]. Still, it is limited to the weighting stage and cannot provide alternative rankings. In contrast, MABAC is known to be capable of producing stable alternative rankings in fuzzy environments [27], although its accuracy is highly dependent on the reliability of the criteria weights used. Recent literature confirms that single MCDM methods tend to provide partial decisions, while hybrid approaches produce more robust results in complex contexts, particularly those related to sustainability [23], [30], [31]. An alternative approach to this gap proposes the Fuzzy BWM-MABAC Multi-Criteria Decision Framework to evaluate and prioritize strategic solutions based on the assessment of loading and unloading factor barriers in ports. By implementing MCDM engineering methods to handle uncertainty [29]. Determining the optimal ranking of alternatives can provide an evaluation of strategic improvements to efficiency and environmental impact. The purpose of this research is to develop an evaluation model using the Fuzzy BWM method for assessing the weight of obstacles to loading and unloading process factors at the port, and to utilize Fuzzy MABAC to provide decision-making insights and propose strategic improvements in enhancing port operations and sustainability[24, 30].

Methods

Proposed Procedure

This research uses a *Multi-Criteria Decision Making* (MCDM) based approach in an uncertain environment (fuzzy environment). The sub-criteria of bottlenecks in port loading and unloading activities were adapted from Mombeni *et al.* [29]. The primary objective was to identify and evaluate the operational bottlenecks in loading and unloading activities at the port by ranking six key strategies and using a combination of *Fuzzy Best Worst Method* (F-BWM) [24] for weighting obstacle criteria and *Fuzzy Multi-Attributive Border Approximation Area Comparison* (F-MABAC) [31] to evaluate alternative strategies. The first stage involves identifying the framework of factors that hinder the effectiveness of loading and unloading at the port [32] and the opinions of several experts. In the second stage, expert preferences were collected by determining the best and worst criteria in a *Focus Group Discussion*, which was then followed by a linguistic assessment of the obstacle criteria. In the third stage, the weights of each obstacle criterion were calculated using the F-BWM method to obtain fuzzy logic-based priorities. In the fourth stage, six alternative strategies for improving effectiveness were formulated based on the identified problems. In the fifth stage, the strategies were assessed against 25 constraint criteria using a fuzzy linguistic scale by experts. In the sixth stage, the strategies were ranked using the F-MABAC method, which involved normalization, weighting, calculation of distance to boundary area (BAA), defuzzification, and summation of scores, to determine the most effective strategy.

This study begins with the identification of factors that hinder the effectiveness of the loading and unloading process based on literature reviews and focus group discussions with experts. After that, the best and worst criteria are determined using the Fuzzy Best-Worst Method (F-BWM) to obtain the weights of the identified inhibiting factors. The weights obtained were used as a basis for formulating strategies to improve loading and unloading effectiveness, which were then evaluated using these weighted criteria. Next, the Fuzzy MABAC method was applied to rank the strategy, thereby identifying the most appropriate alternatives for improving the efficiency and sustainability of loading and unloading operations at the port.

Model Formulation

Fuzzy BWM

This study adopts Triangular Fuzzy Numbers (TFN) due to their simplicity in representing linguistic uncertainty with only three parameters (l, m, u), as well as their higher computational efficiency compared to trapezoidal or Gaussian fuzzy numbers. TFN allows for easy conversion of linguistic perceptions into numerical form, making it suitable for studies involving multiple evaluation criteria. Several previous studies have also demonstrated the successful application of TFN in the context of ports and logistics. For example, TFN-based fuzzy TOPSIS was used for port selection considering environmental factors [13], while it was applied to the selection of dry bulk cargo ships [22], Furthermore, TFN was integrated with Fuzzy BWM and MABAC in evaluating sustainable transportation [24], demonstrating that TFN can improve the reliability of results in hybrid MCDM models. As a result, the use of TFN in this study is considered relevant and consistent with previous research practices in the field of fuzzy MCDM.

Fuzzy BWM is used to provide an assessment of obstacles based on expert opinions. The first step is to determine several criteria $\{C1, C2, \ldots, Cn\}$ that are relevant and influential in the decision-making process. Next, choose the best and worst criteria that will be compared against all other criteria using the triangular fuzzy numbers listed in Table 1. Then compile a fuzzy optimization model to determine the optimal weight of each criterion (w_j) that minimizes the maximum deviation (ξ) as in Equation (1), which is the biggest difference between the actual weight and the weight of the fuzzy preference conversion result. The first constraint, as in Equation (1a), ensures that the difference between the weight of the best criterion (w_B) and the preference ratio($w_j\,'$) against each criterion does not exceed the deviation limit (ξ). The second constraint in Equation (1b) limits the difference between the actual weight (w_j) and the preference ratio of the criterion (j) against the worst criterion($w_j\,''$), to stay within the deviation tolerance limit (ξ). At the same time, the third constraint in Equations (1c and 1d) ensures that the preference value is within the upper and lower limits according to the confidence level (α). In Equation (1e), this constraint ensures that the sum of all criterion weights equals one. This is important so that the weights can be interpreted on a proportional scale. Equation (1f) states that all criterion weights cannot be negative. Finally, it calculates the consistency value (CR) where ξ^* is the optimal deviation value of the model is as in Equation (2), and CI is the consistency index based on the number of criteria. If this is the case $CR \leq 0.1$, then the weights are considered consistent.

Table 1. Fuzzy BWM scale

Linguistic Variables	Triangular Fuzzy Numbers
Equal	(1,1,1)
Weak advantage	(1,2,3)
Not bad	(2,3,4)
Preferable	(3,4,5)
Good	(4,5,6)
Fairly good	(5,6,7)
Very good	(6,7,8)
Absolute	(7,8,9)
Perfect	(8,9,10)

List of notations

j	:	index of criteria (j =1, 2 ,…,n)
w_j	:	weight of criterion j
w_B	:	weight of the best criterion
w_W	:	weight of the worst criterion
$w_j\,'$	:	preference ratio of best to criterion j
$w_j\,''$	:	preference ratio of criterion j to worst
ξ	:	maximum deviation variable
α	:	confidence level parameter
ξ^*	:	optimal value of deviation variable
CR	:	consistency ratio
CI	:	consistency index

$$min\ \xi \quad (1)$$
$$|\, w_B - w_j^{'} \,| \leq \xi ,\forall j \quad (1a)$$
$$|w_j - w_j^{''}| \leq \xi ,\forall j \quad (1b)$$
$$(l_{Bj} + (m_{Bj} - l_{Bj})\alpha)w_j \leq w_j^{'} \leq (u_{Bj} - (u_{Bj} - m_{Bj})\alpha)w_j, \forall j \quad (1c)$$
$$(l_{jw} + (m_{jw} - l_{jw})\alpha)w_W \leq w_j\,'' \leq (u_{jw} - (u_{jw} - m_{jw})\alpha)w_W, \forall j \quad (1d)$$

$\sum_j w_j = 1$ (1e)
$w_j \geq 0$ (1f)
$CR = \frac{\xi^*}{CI}$ (2)

Fuzzy MABAC

Table 2. Fuzzy MABAC scale

Linguistic Variables	Triangular Fuzzy Numbers
Very Low	(1,1,2)
Low	(1,2,3)
Medium	(2,3,4)
High	(3,4,5)
Very High	(4,4,5)

Followed by the Fuzzy MABAC method to select alternative strategies for the loading and unloading process. The fuzzy MABAC scale is presented in Table 2. The first step in the Fuzzy MABAC method is to compile a fuzzy decision matrix ($\tilde{X}$) as in Equation (3) which shows the performance value of the i-th alternative against the j-th criterion where the matrix is $m \times n$ as in Equation (4), m is the number of alternatives and n is the number of criteria. In Equation (5) normalize($\tilde{N}$) against the fuzzy matrix ($\tilde{X}$) , so that the value of each alternative is on a scale of 0 to 1. For *benefit* criteria in Equation (6), higher values indicate better preferences, while *cost* criteria in Equation (7), smaller values are more desirable. The next step calculates the weighted decision matrix ($\tilde{v}_{ij}$) as in Equation (8), the normalized fuzzy value($w_i \tilde{t}_{ij}$) is multiplied by the fuzzy weights resulting from the fuzzy BWM (w_i). Equation (9) contains the expert's fuzzy assessment of the BWM fuzzy weights that show the performance of the alternative $i - th$ against the criteria $j - th$, with the linguistic scale converted to TFN. Calculate the *border approximation area* (BAA) value($\tilde{g}_i$) for each criterion as in (10).

For Equation (11), it is a two-line vector displaying the criterion name on the first line and the boundary area value($\tilde{g}_i$) on the second line. The notation $\tilde{G}$ is used to express the structure of the boundary approach area for all criteria. Then, calculate the distance matrix Q by calculating the difference between the value $\tilde{v}_{ij}$ and the BAA value ($\tilde{g}_i$) for each alternative and criterion. In Equation (12), the value of $\tilde{q}_{ij}$ indicates the distance between the i-th alternative and the ideal limit on the j-th criterion. In Equation (13) the matrix $\tilde{Q}$ is the result of the reduction between the weighted matrix ($\tilde{V}$) and the value of the boundary approach area ($\tilde{G}$). Equation (14) determines the location of the alternative $\tilde{A}_i$ against the boundary approach area. If the value $\tilde{q}_{ij}$ is positive, then the alternative is better than the boundary value, if zero then it is equivalent to the boundary, and if negative then the alternative is below the boundary standard. Continue to calculate the total difference value for each alternative by summing up all $\tilde{Q}$ values as in Equation (15). After obtaining a fuzzy score in the form of $\tilde{S}_i$, it is necessary to do defuzzification to get a value that can be compared as in Equation (16) which is one of the defuzzification methods is the Center of Area (COA) method to convert triangular fuzzy values (t_1, t_2, t_3) into crisp values. This defuzzification calculates an average that considers the lower and upper widths of the fuzzy triangle. The last step performs the ranking of alternatives based on the value S , where the highest value indicates the best alternative allowing for the analysis of the ranking results as a basis for objective and measurable decision recommendations.

The combination of the Fuzzy BWM-MABAC method provides a detailed framework in the decision-making process. F-BWM plays a role in objectively determining the weights of obstacle criteria, while F-MABAC is used to calculate the final score and rank alternative strategies based on the weight of obstacles and their respective performance. Therefore, the Fuzzy BWM-MABAC method is considered effective and stable to be used in various studies involving many criteria and choices.

List of notations:

$\tilde{X}$	:	fuzzy decision matrix
m	:	number of alternatives
n	:	number of criteria
$\tilde{N}$	:	normalize fuzzy decision matrix
$\tilde{v}_{ij}$	:	weighted decision matrix

$w_i\tilde{t}_{ij}$	:	normalized fuzzy value
$\tilde{g}_i$	:	boundary area value
$\tilde{q}_{ij}$	:	distance between alternative i and BAA on criterion j
$\tilde{S}_i$	:	overall fuzzy score of alternative i
$\tilde{G}$	:	boundary approach area
$\tilde{A}_i$	:	fuzzy performance value of alternative i on criterion j

$$\tilde{X} = [x_{ij}] \tag{3}$$

$$\tilde{X} = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{matrix} C_1 \; C_2 \; \dots \; C_n \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{11} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \vdots & \vdots & \dots & \vdots \\ \tilde{x}_{1m} & \tilde{x}_{2m} & \dots & \tilde{x}_{mn} \end{bmatrix} \end{matrix} \tag{4}$$

$$\tilde{N} = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{matrix} C_1 \; C_2 \; \dots \; C_n \\ \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \dots & \tilde{t}_{1n} \\ \tilde{t}_{11} & \tilde{t}_{22} & \dots & \tilde{t}_{2n} \\ \vdots & \vdots & \dots & \vdots \\ \tilde{t}_{1m} & \tilde{t}_{2m} & \dots & \tilde{t}_{mn} \end{bmatrix} \end{matrix} \tag{5}$$

$$\tilde{t}_{ij} = \frac{x_{ij}-x_i^-}{x_i^+-x_i^-} \tag{6}$$

$$\tilde{t}_{ij} = \frac{x_{ij}-x_i^+}{x_i^+-x_i^+} \tag{7}$$

$$\tilde{v}_{ij} = w_i(\tilde{t}_{ij}+1) = w_i\tilde{t}_{ij}\otimes w_i \tag{8}$$

$$\tilde{V} = \begin{bmatrix} \tilde{v}_{11} & \tilde{v}_{12} & \dots & \tilde{v}_{1n} \\ \tilde{v}_{21} & \tilde{v}_{22} & \dots & \tilde{v}_{2n} \\ \vdots & \vdots & \dots & \vdots \\ \tilde{v}_{m1} & \tilde{v}_{m2} & \dots & \tilde{v}_{mn} \end{bmatrix} \tag{9}$$

$$\tilde{g}_i = \left(\prod_{j=1}^{m} \tilde{v}_{ij}\right)^{1/m} \tag{10}$$

$$\tilde{G} = \begin{matrix} C_1 \; C_2 \; \dots \; C_3 \\ [\tilde{g}_1 \; \tilde{g}_2 \; \cdots \; \tilde{g}_n] \end{matrix} \tag{11}$$

$$\tilde{Q} = \begin{bmatrix} \tilde{q}_{11} & \tilde{q}_{12} & \cdots & \tilde{q}_{1n} \\ \tilde{q}_{21} & \tilde{q}_{22} & \cdots & \tilde{q}_{2n} \\ \vdots & \vdots & \dots & \vdots \\ \tilde{q}_{m1} & \tilde{q}_{m2} & \cdots & \tilde{q}_{mn} \end{bmatrix} \tag{12}$$

$$\tilde{Q} = \tilde{V} - \tilde{G} \tag{13}$$

$$\tilde{A}_i \in \begin{cases} \tilde{G}^+ \; if \; \tilde{q}_{ij} > 0 \\ \tilde{G} \; if \; \tilde{q}_{ij} = 0 \\ \tilde{G}^- \; if \; \tilde{q}_{ij} < 0 \end{cases} \tag{14}$$

$$\tilde{S}_i = \sum_{j=1}^{n} \tilde{q}_{ij}, j = 1,2,\dots,n, i = 1,2,\dots,m \tag{15}$$

$$Defuzzy\ S = [(t_3 - t_1) + (t_2 - t_1)]3^{-1} + t_3 \tag{16}$$

Data and Case Study

This research focuses on assessing barriers and prioritizing strategies at ports through the application of the Fuzzy BWM-MABAC method. A total of 25 sub-criteria for barriers were identified based on a literature review of various scientific journals and are presented in Table 3. However, before implementation, a validation and modification process was carried out by a panel of experts. The validation results showed that all sub-criteria were relevant, although some terms were adjusted to make them more contextually relevant. Thus, this study maintained the same number of sub-criteria to ensure consistency with previous studies but adapted the terminology to suit local conditions.

All sub-criteria of obstacles were classified as benefits or costs, depending on their impact on port performance. The priority weight of the obstacle criteria was determined using the Fuzzy BWM Method, which involved three experts from different backgrounds. The roles of the three experts in this study complemented each other. An academic contributed methodologically and theoretically, while an operational manager provided strategic insights related to policy and resource allocation. An operational supervisor also provided input based on technical experience in the field. This composition was chosen to ensure that the criteria for weighting and strategy evaluation processes reflect a balance between academic, strategic, and technical perspectives. This case study examines the general characteristics of ports facing similar challenges, such as waiting times, equipment availability, and labor, without specifically referring to any port. Although the number of experts involved was limited to three, this composition was deemed adequate as it was able to represent a variety of relevant perspectives. Thus, the assessment results can still be considered representative of the actual conditions of loading and unloading operations at ports.

Table 3. Identification of barriers criteria and sub-criteria

Dimension	Code	Barrier criteria	Type
Port	C1	Dock cleaning	Cost
	C2	Delay in starting up	Cost
	C3	Lack of traction in warehouse and field	Cost
	C4	Contractor unpreparedness	Cost
	C5	Ship entry and quarantine procedures	Benefit
	C6	Shore transport equipment breakdown	Cost
	C7	Breakdown of loading and unloading equipment	Cost
	C8	Incapacity of unloading equipment	Cost
	C9	Lack of skilled workers	Cost
	C10	Insufficient standard compliance	Cost
	C11	Information technology capability	Benefit
	C12	Efficient in handling customer complaints	Benefit
Ship operation	C13	Warehouse opening and closing in ship operation	Benefit
	C14	Balance adjustment in ship operation	Benefit
	C15	Cleaning in ship operation	Cost
	C16	Lack of readiness in ship operation	Cost
	C17	Displacement in ship operation	Benefit
Freight owners and agents outside the port	C18	Lack of readiness of the owner of the goods	Cost
	C19	Customs formalities	Benefit
	C20	Documentation and financial issues (related to ship, cargo owner, customs, and cargo terminal)	Cost
	C21	Lack of trucks	Cost
Atmospheric factors	C22	Unfavorable weather	Cost
	C23	Unpreparedness of beach transport equipment due to weather conditions	Cost
	C24	Poor visibility of crane operator	Cost
	C25	Lack of safety when loading and unloading goods	Cost

Table 4. Expert assessment of fuzzy MABAC loading and unloading process alternative strategies

Sub-Criteria	Expert 1						Expert 2						Expert 3					
	S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6
C1	H	H	L	VH	M	M	H	H	H	VH	L	M	VH	L	M	VH	H	L
C2	L	VH	H	L	M	H	L	VH	M	M	M	H	M	VH	M	H	H	L
C3	L	L	VH	L	M	M	M	L	VH	H	M	M	L	L	VH	M	H	H
C4	L	H	L	H	M	L	H	L	M	H	L	M	M	M	H	VH	H	H
C5	L	H	H	M	H	L	H	L	H	L	H	M	M	H	L	H	VH	L
C6	VH	H	M	M	M	H	VH	L	H	H	M	H	VH	H	L	L	M	H
C7	VH	M	M	H	H	H	VH	L	H	H	L	L	VH	L	M	M	M	M
C8	L	H	H	H	H	L	H	H	H	L	H	L	M	H	H	H	H	L
C9	H	L	VH	L	M	M	L	M	H	M	M	L	L	M	H	H	M	H
C10	L	H	H	H	L	M	L	M	M	VH	L	M	M	M	H	H	L	M
C11	H	M	M	M	VH	L	M	H	L	H	VH	L	M	M	M	L	VH	L
C12	H	M	H	H	L	VH	M	M	L	H	M	VH	M	H	L	M	M	H
C13	H	H	M	L	M	H	VH	L	M	H	L	M	VH	H	L	M	L	L
C14	H	VH	L	H	H	L	M	VH	L	L	L	M	L	VH	M	L	L	M
C15	M	L	VH	L	L	L	L	M	H	L	L	M	L	H	VH	M	M	M
C16	M	L	M	H	H	L	L	M	M	H	L	M	L	H	M	H	H	H
C17	L	H	H	L	H	M	H	M	M	M	H	M	M	L	H	L	VH	L
C18	H	H	L	M	M	VH	M	H	M	L	L	VH	L	H	L	M	L	H
C19	VH	H	M	L	L	L	VH	H	L	H	M	L	VH	M	M	H	L	L
C20	L	H	M	L	H	M	M	VH	M	L	H	M	M	VH	H	H	H	M
C21	H	M	H	H	L	M	L	M	H	L	H	M	L	H	H	M	L	L
C22	M	H	M	H	M	L	M	L	M	VH	M	M	M	L	H	VH	L	H
C23	L	H	L	M	H	L	H	L	M	M	H	H	H	H	L	H	VH	H
C24	L	L	H	M	H	H	L	H	M	L	M	H	H	L	H	L	M	H
C25	H	L	L	L	H	VH	VH	L	M	M	H	VH	VH	H	H	L	L	VH

Each expert identified the best and worst criteria, then provided linguistic assessments of the other criteria, as shown in Appendix A. These values were converted into triangular fuzzy numbers and processed in the F-BWM optimization model to obtain consistent fuzzy weights that could be interpreted quantitatively. Six alternative strategies for improving operational effectiveness were formulated and presented in Appendix B, covering technical, procedural, and other supporting aspects. The six alternative strategies identified are the result of a systematic review of previous studies on port operational efficiency [20] [32] and were then adapted to the port context and expert discussions. Some strategies appear to combine two different aspects, such as "equipment modernization and preventive maintenance systems." This combination reflects actual practices in modern ports, where equipment modernization is almost always accompanied by the integration of predictive maintenance [28]. Similarly, warehouse layout reorganization is usually accompanied by increased human resource competency to ensure the sustainability of process changes. Therefore, combined strategies are seen as a representation of realistic practices, not merely theoretical constructions. The assessment of each strategy's contribution to the 25 limiting sub-criteria was carried out by three experts using a fuzzy linguistic scale, as shown in Table 4. Further analysis was performed using the Fuzzy MABAC Method to determine the most effective strategy based on the highest total score.

Results and Discussions

In this study, the consistency of expert assessments was verified by calculating the Consistency Ratio (CR) using the Fuzzy BWM method. The results shown in Table 5 indicate that all CR values are ≤ 0.1, meaning that the criteria obtained show a highly consistent assessment. The weighting process through the Fuzzy BWM Method yields a priority distribution that reflects the expert's perception of the bottleneck factors most affecting the effectiveness of loading and unloading operations at the Port in Table 6. The results show that the criterion with the highest weight is balance adjustment in ship operations (C14) at 0.149, followed by lack of readiness in ship operations (C16), warehouse opening and closing in ship operations (C13), and transfer in ship operations (C17). These four criteria are aspects that occur directly in the operational phase of the vessel and are considered the main sources of loading and unloading time inefficiencies. In contrast, the two criteria that received the lowest weights were poor visibility for crane operators (C24) and a lack of security during loading and unloading goods (C25). While important in terms of safety and convenience, these aspects are considered to have less direct influence on the overall efficiency or speed of the loading and unloading process.

Table 5. Consistency ratio across expert assessments

Expert	CR Value
1	0,0144
2	0,0083
3	0,0119

Table 6. Fuzzy BWM obstacle sub-criteria weighting results

Code	Sub-criteria	Weight	Rank
C1	Dock cleaning	0.014	22
C2	Delay in starting	0.018	19
C3	Lack of traction in warehouse and field	0.027	12
C4	Contractor unpreparedness	0.016	21
C5	Ship entry and quarantine procedures	0.027	11
C6	Shore transport equipment malfunction	0.022	16
C7	Unloading equipment malfunction	0.074	5
C8	Inability of unloading equipment	0.025	13
C9	Lack of skilled workers	0.020	17
C10	Inadequate standards compliance	0.031	9
C11	Information technology capability	0.033	6
C12	Efficient in handling customer complaints	0.032	7
C13	Warehouse opening and closing in ship operation	0.106	3
C14	Balance adjustment in ship operation	0.150	1
C15	Cleaning in ship operation	0.031	8
C16	Lack of readiness in ship operation	0.128	2
C17	Displacement in ship operation	0.094	4
C18	Lack of readiness of the owner of the goods	0.025	14
C19	Customs formalities	0.023	15
C20	Documentation and financial issues	0.028	10
C21	Lack of trucks	0.019	18
C22	Unfavorable weather	0.017	20
C23	Unpreparedness of transport equipment due to weather	0.014	23
C24	Poor visibility of crane operator	0.010	25
C25	Lack of security when loading and unloading goods	0.014	24

This weight distribution reflects that technical and procedural barriers in the ship area are more influential than environmental or personnel factors. This can be justified by the characteristics of the port in the case study, which focuses on export-import activities with high operational intensity of ships.

Alternative strategies for the Loading and Unloading Process are calculated using the Fuzzy MABAC method with the weighted barriers of the F-BWM results. This process produces a defuzzification score for each strategy based on the reference value of the total deviation of the border approximation area (BAA). The evaluation results in Table 7 show that the Modernization of Loading and Unloading Equipment and Preventive Maintenance System (S1) strategy obtained the highest total score and was ranked first overall. This strategy is considered the most impactful intervention because it can overcome the main obstacles arising from the criteria with the highest weights, namely, technical limitations and operational readiness on the ship. Equipment modernization not only increases the physical capacity for loading and unloading but also speeds up the process, minimizes waiting time, and reduces the potential for damage to goods.

The SOP Standardization and Digitalization of Ship Pre-Operation Procedures (S2) and Integrated E-Document System (S5) strategies followed in second and third place. This second strategy provides solutions to procedural and documentation aspects that are considered crucial but not dominant. This ranking suggests that administrative efficiency plays a significant role, but its impact is still less pronounced than that of direct technical solutions. Meanwhile, the Warehouse Layout Reorganization and Human Resource Improvement (S3) strategies consistently ranked the lowest. This suggests that long-term or indirect interventions to shipping activities have less impact when the problem at hand is urgent and operational in nature.

Table 7. Ranking results of alternative strategies for the loading and unloading process

Strategy	1	2	3	4	5	6
Result	0.115	0.099	-0.046	-0.050	0.036	-0.010

Sensitivity Analysis

To test the stability and robustness of the decision-making model built, a sensitivity analysis of the constraint weight criteria is presented in Table 8. This analysis aims to determine the extent to which the results of strategy ranking are affected by changes in decision-makers' preferences, especially in terms of the distribution of weights between constraint criteria, as visualized in Figure 1. Five scenarios are systematically designed to represent the various possible configurations of constraint weights that can occur in management practice.

Table 8. Sensitivity analysis of alternative strategies

Strategy	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank
1	0.115	1	0.129	1	0.114	1	0.096	1	0.124	1
2	0.099	2	0.097	2	0.101	2	0.056	3	0.025	4
3	-0.046	5	-0.050	6	-0.047	5	-0.043	6	-0.074	6
4	-0.050	6	-0.046	5	-0.051	6	0.005	4	0.039	3
5	0.036	3	0.019	3	0.036	3	0.060	2	0.074	2
6	-0.010	4	-0.010	4	-0.010	4	-0.008	5	-0.018	5

In Scenario 1, the weight of the criterion with the highest contribution in the base model, namely balance adjustment in ship operations (C14), was increased by 20%. This scenario represents a situation where port management prioritizes ship operational stability as a top strategic priority. The results showed that strategy S1 remained at the highest position, indicating that the technical advantages of the strategy remained relevant even though the weight of the dominant criterion was increased. The ranking of other strategies also remained relatively unchanged. Scenario 2 tested the opposite condition, reducing the weight of the delayed start criteria (C2) by 20%. This criterion was previously not in the top five based on its initial weight. The results showed that this change had almost no impact on the ranking of strategies, proving that low-weight criteria have limited influence on the results, and the model is quite resilient to small changes.

Scenario 3 used an even weight distribution approach for all criteria. This scenario is meant to document a condition where policymakers do not give special preference to any aspect but assess all criteria equally. In this configuration, strategies S2 and S5 saw an increase in scores, but S1 still maintained the highest ranking. This

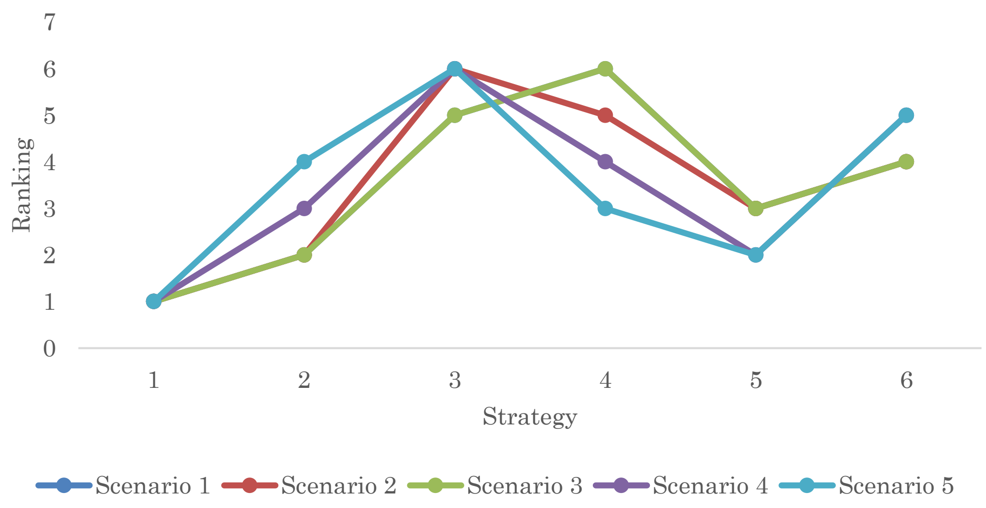

Figure 1. Sensitivity analysis of alternative strategy selection

demonstrates that the advantage of strategy S1 is comprehensive and does not depend solely on one or two key criteria. Scenario 4 focuses on increasing the weight of criteria related to technology and digitization, such as information technology capabilities (C11), complaint handling efficiency (C12), and financial documentation and issues (C20). The objective of this scenario is to shift managerial orientation towards digital transformation. The results show a significant improvement in the scores of strategies S2 and S5, which are focused on digitization processes and system integration. Although S1 remains in the lead in total score, the gap between strategies becomes narrower.

Scenario 5 adopts an extreme approach by simultaneously increasing the weight of two key criteria: the opening and closing of warehouses in ship operations (C13) and balance adjustment (C14), thereby bringing their total weight to more than 50%. This reflects a situation where management has a very short policy focus. Overall, the sensitivity analysis confirms that the model has high robustness to moderate variations in weight distribution. Strategy S1 consistently outperforms in five out of five scenarios, which reinforces its validity as the most effective strategy in general. However, the model's ability to reflect changes in priorities in extreme scenarios also demonstrates the Fuzzy MABAC method's support for adaptive and dynamic decision-making in complex port environments.

The S3 strategy shows lower performance for several reasons. First, reorganizing the layout and training human resources tends to produce medium to long-term benefits. This aligns with the importance of the social dimension in port sustainability [12], including the readiness and competence of the workforce, which require time to implement. Additionally, capacity building and transformation in port management also pose challenges for human resources, as demonstrated by the fact that improving port capacity and service quality requires significant competency adaptation [2]. Meanwhile, technology and operation-based interventions have been proven to provide faster efficiency improvements, as demonstrated by the importance of technical and operational improvements in reducing loading and unloading delays [32] [33]. Therefore, the low S3 ranking is not due to irrelevance, but rather because of its immediate impact in reducing loading and unloading bottlenecks.

The findings of this study provide several practical insights for port managers and policymakers. The integrated Fuzzy BWM–MABAC framework enables decision-makers to prioritize strategies under uncertainty by combining the objective weights of criteria with the multi-criteria rankings of alternatives. Through this approach, managers can allocate limited resources more effectively to interventions that have the highest and most direct impact on port efficiency. Further analysis shows that strategies such as modernizing loading and unloading equipment and implementing preventive maintenance systems consistently yield better performance than other options. This suggests that technology- and equipment-based improvements should be prioritized as interventions, as investments in modernization can provide immediate and tangible benefits in turnaround time and service reliability. On the other hand, initiatives related to human resource competency development and warehouse layout reorganization tend to produce results over a longer period. Lower relative rankings do not indicate a lack of relevance but rather reflect the fact that these measures take longer to produce visible benefits. These strategies should be positioned as medium- to long-term complements, ensuring that workforce development and infrastructure redesign are aligned with ongoing digitization and equipment upgrades.

Conclusion

This study developed a multicriteria decision-making framework based on the Fuzzy BWM-MABAC method for evaluating the effectiveness of port loading and unloading operational strategies. In the context of complex and short-term port systems, this approach proves its ability to harmonize qualitative and quantitative evaluations systematically and adaptively. The main findings of this study indicate that the effectiveness of strategy is highly dependent on managerial prioritization of key criteria. Strategy S1 consistently outperforms in the base weight configuration, indicating that technical solutions have the most direct impact on operational efficiency. Methodologically, this study contributes to the understanding of Fuzzy BWM-MABAC trade-offs in logistics sector strategic decision-making. Adjustments to the normalization process and the use of weighted weights make the model more responsive to changing preferences. In addition, the five-scenario sensitivity approach used demonstrates that the framework is not only reliable under normal conditions but also flexible in response to relevant changes in the dynamic port management context. From a practical perspective, the model can be implemented as a policy simulation tool for periodic decision-making. Port managers can use the evaluation results as a basis for designing investment priorities, reorganizing operational procedures, and developing medium-term strategies in line with the dynamics of the maritime industry.

Based on these findings, port authorities are advised to prioritize investment in automation and modernization of loading and unloading equipment, as this measure can quickly and significantly improve operational performance and service reliability. At the same time, it is necessary to develop structured programs for training and improving human resource competencies, so that workers are able to adapt to new technologies and digital systems. Aligning technological improvements with gradual human resource development will create balanced and sustainable improvements in port performance, both in the short and long term. Recommendations for further research include incorporating constraint criteria that consider environmental and desire dimensions, testing the model in ports with different characteristics (e.g., logistics ports and dry bulk ports), and integrating the method with optimization or machine learning approaches for more automated and predictive decision-making.

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Appendix

Appendix A. Fuzzy BWM barriers sub criteria assessment

Code	Best to Others (Expert 1)	Others to Worst (Expert 1)	Best to Others (Expert 2)	Others to Worst (Expert 2)	Best to Others (Expert 3)	Others to Worst (Expert 3)
C1	(3,4,5)	(4,5,6)	(5,6,7)	(4,5,6)	(5,6,7)	(6,7,8)
C2	(4,5,6)	(4,5,6)	(3,4,5)	(6,7,8)	(6,7,8)	(4,5,6)
C3	(2,3,4)	(3,4,5)	(4,5,6)	(5,6,7)	(4,5,6)	(3,4,5)
C4	(5,6,7)	(3,4,5)	(5,6,7)	(4,5,6)	(3,4,5)	(5,6,7)
C5	(3,4,5)	(4,5,6)	(4,5,6)	(3,4,5)	(4,5,6)	(3,4,5)
C6	(6,7,8)	(5,6,7)	(3,4,5)	(6,7,8)	(6,7,8)	(5,6,7)
C7	(1,1,1)	(5,6,7)	(1,1,1)	(6,7,8)	(1,1,1)	(5,6,7)
C8	(2,3,4)	(2,3,4)	(3,4,5)	(8,9,10)	(8,9,10)	(6,7,8)
C9	(4,5,6)	(3,4,5)	(5,6,7)	(6,7,8)	(6,7,8)	(5,6,7)
C10	(2,3,4)	(2,3,4)	(3,4,5)	(4,5,6)	(3,4,5)	(3,4,5)
C11	(2,3,4)	(3,4,5)	(2,3,4)	(5,6,7)	(5,6,7)	(3,4,5)
C12	(3,4,5)	(4,5,6)	(3,4,5)	(3,4,5)	(3,4,5)	(2,3,4)
C13	(5,6,7)	(5,6,7)	(5,6,7)	(2,3,4)	(2,3,4)	(3,4,5)
C14	(2,3,4)	(3,4,5)	(3,4,5)	(3,4,5)	(3,4,5)	(2,3,4)
C15	(8,9,10)	(1,1,1)	(8,9,10)	(1,1,1)	(8,9,10)	(1,1,1)
C16	(3,4,5)	(3,4,5)	(3,4,5)	(2,3,4)	(3,4,5)	(2,3,4)
C17	(5,6,7)	(5,6,7)	(5,6,7)	(3,4,5)	(2,3,4)	(3,4,5)
C18	(4,5,6)	(4,5,6)	(5,6,7)	(3,4,5)	(3,4,5)	(3,4,5)
C19	(5,6,7)	(3,4,5)	(3,4,5)	(6,7,8)	(5,6,7)	(4,5,6)
C20	(3,4,5)	(3,4,5)	(4,5,6)	(4,5,6)	(3,4,5)	(3,4,5)
C21	(5,6,7)	(4,5,6)	(5,6,7)	(5,6,7)	(5,6,7)	(5,6,7)
C22	(5,6,7)	(3,4,5)	(3,4,5)	(5,6,7)	(3,4,5)	(3,4,5)
C23	(3,4,5)	(4,5,6)	(4,5,6)	(4,5,6)	(4,5,6)	(3,4,5)
C24	(5,6,7)	(5,6,7)	(5,6,7)	(3,4,5)	(3,4,5)	(5,6,7)
C25	(4,5,6)	(3,4,5)	(3,4,5)	(6,7,8)	(4,5,6)	(4,5,6)

Appendix B. Alternative strategy of fuzzy MABAC loading and unloading process

Code	Strategy
S1	Modernization of Loading and Unloading Equipment and Preventive Maintenance System
S2	Standardization of SOPs and Digitalization of Ship Pre-Operation Procedures
S3	Warehouse Layout Reorganization and HR Competency Improvement Program
S4	Dock Cleaning Scheduling and Quarantine Integration
S5	E-Document System Integrated with Customs and Quarantine
S6	Crane Operation Safety and Visibility System Improvement