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Proposing Key Factors to Deploy Vietnam E-Navigation Model Using Fuzzy-AHP Multi-criteria Approach

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Abstract: E-Navigation is considered a fundamental solution for digital transformation in the Vietnamese maritime industry. In this paper, the authors propose a practical framework for assessing Vietnam's current readiness for e-Navigation. The main factors for assessment include: Governance and Standardization, Technology Infrastructure, People and Processes, and Information and Data. Furthermore, these four main factors are assessed in detail according to thirteen factors that have been refined based on international guidelines and expert analysis and evaluation. Since expert analysis and evaluation may be uncertain, to determine the relative weights of the factors, the Fuzzy Analytical Hierarchy Process (Fuzzy-AHP) was applied. The results show that the main factor of Governance and Standardization has the highest weight. This is followed by the factors of Technology Infrastructure and People, respectively. The results of this assessment indicate the hierarchical harmonization of the criteria which will be an important basis for maritime state management agencies and related organizations in developing e-Navigation development plans in Vietnam. In the future, this assessment method can be referenced and adjusted to develop e-Navigation for countries with similar conditions.

Keywords: Fuzzy-AHP method, maritime digital infrastructure, Vietnam e-Navigation.

1. INTRODUCTION

The International Maritime Organization (IMO) e-Navigation initiative is considered a fundamental solution in the digital transformation process to improve maritime safety, security and marine environmental protection in maritime operations [1-3]. In December 2005, at the 81st session of the Maritime Safety Committee (MSC) of the IMO, the United Kingdom, the United States, Japan, Norway, the Netherlands, the Marshall Islands and Singapore were the member countries that proposed to include e-Navigation in the work program of the Maritime Safety Subcommittee (NAV) and the Radio communication and Search and Rescue Subcommittee (COMSAR). Accordingly, a strategic vision was developed to harmonize the application of existing and future maritime technology equipment to minimize accidents and human errors by establishing a set of standards for e-Navigation to ensure safety, security and environmental protection.

The MSC subsequently adopted Resolution MSC.81(5/2006), which formally introduced the concept of e-Navigation into its documentation. In November 2008, the MSC approved the e-Navigation Strategy, developed an implementation plan, and provided a definition in Resolution MSC.85 as follows: "*e-Navigation is the collection, integration, exchange, presentation and analysis of maritime information on board and ashore by electronic means to enhance berth-to-berth navigation and related services, for safety and security at sea and protection of the marine environment*" [4]. In 2009, the MSC endorsed a proposal for a coordinated approach to the implementation of the e-Navigation strategy. At the 57th session of the Sub-Committee on Safety of Navigation (NAV 57) on 10 June 2011, the IMO Secretary-General reaffirmed that in-depth studies were ongoing and that a global strategy for e-Navigation was under development, stressing the importance of adhering to its vision and objectives to meet the needs of safe and efficient maritime transportation in the 21st century.

Vietnam, with a coastline exceeding 3,260 km stretching across 13 latitudes, holds a geopolitically strategic position in Asia. Its seaports form critical links in major maritime trade routes connecting the Indian Ocean and the Pacific, as well as Europe and the Middle

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Research article

Table 1. Detailing important factors for evaluation.

Upper level		Lower level	
Governance and standardization	C1	Governance	C11
		Standardization	C12
		Legal framework	C13
Technological infrastructure	C2	Onboard	C21
		Onshore	C22
		Communication infrastructure	C23
Information and data	C3	Collection	C31
		Integration	C32
		Exchange	C33
		Presentation	C34
		Analysis	C35
Human and procedures	C4	Users	C41
		Operational procedures	C42

East with China, Japan, and other regional economies. The maritime industry in Vietnam has been growing strongly in recent times, the need to enhance the capacity to manage, monitor and coordinate modern waterway traffic is very urgent. At the same time, providing digital maritime services following the trend of the international maritime industry such as e-Navigation is an inevitable requirement of development [5-8].

To deploy the e-Navigation model in Vietnamese waters, it is necessary to analyze and integrate many factors. Firstly, the requirement to enhance maritime safety is an urgent issue for the Vietnamese maritime industry. Vietnam's transport activities have increased impressively in recent years, increasing by 8-10% annually, which means that the number of ships has increased sharply, concentrated in gateway areas such as Hai Phong City and Ho Chi Minh City. As a result, the traffic management system is overloaded, increasing the risk of unsafety, channel congestion, and accidents that are mainly due to human error, according to IMO 70-80%. Advanced models such as E-Navigation, combined with modern, highly reliable real-time support technologies, will minimize risks and improve maritime safety [6-8].

Second, the increasing demand for marine environmental protection is a strategic priority for the maritime industry. Vietnam's marine economy plays an important role in the national economy throughout the history of Vietnam's development, these activities often contribute more than 20% of GDP. However, pollution from marine economic activities such as oil spills, waste, and wastewater from ships are threats to marine ecosystems. The e-Navigation system helps managers closely control the activities of patrol boats in real time, helping to detect abnormal behaviors early, proactively prevent and respond to pollution incidents early, helping to minimize damage from maritime incidents, making an important contribution to the process of sustainable development of Vietnam's marine economy.

Third, applying modern technology to the management and operation of the Vietnamese maritime industry helps optimize resources, increase Vietnam's competitiveness in the region as well as the international maritime industry. The Southeast Asian region, typically Singapore, has invested and strongly developed the maritime industry, applying modern technology to maritime traffic management and developing smart ports. The Vietnamese maritime industry can integrate e-Navigation as an important step to promote comprehensive digital transformation of specific industries such as intelligent traffic coordination, enhancing the exchange of big data between ships and shore and vice versa. This will help stakeholders always be proactive in minimizing human errors, saving resources, and improving operational efficiency. Finally, the implementation of the obligations of member states of IMO conventions is a responsibility and also a driving force for development. IMO and related international organizations such as IALA continuously promote the development of global e-Navigation with the foundation of S-100 to implement digital maritime services and intelligent data reporting, global standardization. This is a prerequisite for integration and development. If the Vietnamese maritime industry is slow to implement, it will be a great disadvantage for the entire industry, especially ships operating on international routes [9]. Developing the Vietnamese maritime industry according to the e-Navigation model will not only contribute to ensuring compliance with the obligations of member states but also demonstrate Vietnam's commitment to a safe and environmentally friendly maritime industry, a modern and sustainable model following global trends.

From the above analysis, it can be seen that developing Vietnam's e-Navigation needs to comprehensively consider the influencing factors and proceed step by step. This model needs to integrate IMO's priority technology such as the S-100 data platform, a system with a user-friendly interface, automatic collection and processing of reporting data, ensuring high reliability of the system. Key factors include investment in information and communication technology (ICT) infrastructure, development of a highly skilled workforce, establishment of a coherent legal framework, and strengthening of international cooperation. The research provides a scientific and practical foundation for policymakers, state management agencies, and enterprises to formulate and implement a national e-Navigation strategy, thereby enhancing the competitiveness and sustainable development of Vietnam’s maritime sector. Accordingly, this study evaluates the key factors for developing an optimal e-Navigation model for Vietnam.

2. RESEARCH METHODOLOGY

Decision support solutions to handle multi-criteria management problems are used by many studies using the Fuzzy-AHP method [10-15]. This method considers the pessimistic factor and the optimal evaluation attitude of the decision expert based on the fuzzy language. The characteristic fuzzy triangular numbers and priority rankings in the evaluation according to the membership functions to measure the equivalent ordinary arithmetic [13-16]. Therefore, the Fuzzy AHP method is used in this study to determine the priority weights of important factors in the implementation model to propose the priority level of important factors in the implementation process of the e-Navigation Model in Vietnam.

2.1. Identifying the important factors

The hierarchical structure of criteria for developing an e-Navigation model encompasses four upper-level categories, each with specific sub-criteria, collectively forming a comprehensive framework for implementation and evaluation (Table 1).

First, Governance and Standardization (C1) plays a central role in coordinating and harmonizing the entire e-Navigation ecosystem. In this group of key factors, the Governance factor (C11) supports managers in orienting development strategies, building policies and implementing laws, and at the same time building an inter-sectoral coordination mechanism, coordinating between relevant parties from service providers to direct port operators and specialized state management units. Standardization (C12) is a particularly important factor to ensure the ability to integrate and communicate data exchange systems smoothly between relevant parties according to international standards of IMO and IALA. The Legal Framework factor (C13) is the basis for implementing standardization and system governance, which will bind relevant parties to comply with system deployment requirements to ensure consistency with national maritime laws and international standards.

Second, the technological infrastructure (C2) is considered the backbone of the e-Navigation system. Ship-based infrastructure (C21) is the equipment systems that directly support the navigation process and decisions in ship operations such as AIS, ECDIS, radar, etc. Shore-based infrastructure (C22) is the management, monitoring, and coordination centers for maritime activities such as Vessel Traffic Services (VTS) and related parties coordinate and supervise implementation. Communication infrastructure (C23) is the bridge connecting the ship-based and shore-based facilities, allowing the safe and reliable exchange of real-time data. Third, Information and Data (C3) is a particularly important raw material for e-Navigation to operate. Collection (C31) helps the collected maritime data to ensure accuracy and timeliness. Integration (C32) helps to unify data for effective interaction across the system, increasing the ability to analyze by value. Exchange (C33) between stations shares necessary information in a safe and timely manner to support quick decision making. User-friendly presentation (C34) helps users understand and operate easily by ensuring intuitive transformation of large, complex data sets into intuitive tables, images, and diagrams. Analysis (C35) uses modern models and advanced analytical techniques to provide clear results, forecasting capabilities to help proactively manage and operate.

Finally, People and Processes (C4) are key factors in operating the e-Navigation system. Users (C41) including ship stations as crew members, shore stations as VTS operators and centers, state management agencies on maritime must be trained and coached to improve their qualifications, skills and ability to adapt to situations for effective operation. Operation Procedures (C42) are designed to build standardized planned exploitation procedures to ensure consistency, safety, environmental protection and efficiency even in emergency situations.

Collectively, these criteria form an interconnected system where governance establishes direction, technology enables capability, information fuels decision-making, and people implement and sustain operations. The balanced development of all these elements is critical for realizing the full potential of e-Navigation in enhancing maritime safety, efficiency, and sustainability.

2.2. Fuzzy AHP methodology

Saaty (1977) has proposed the problem of generalizing the standard set theory to fuzzy sets to minimize the ambiguity and approximation errors [17]. The uncertainty due to ambiguity is more reasonably oriented. In this section, the Fuzzy AHP method is used to determine the final weighting coefficients for the principal factors.

Saaty introduced the multi-criteria decision making tool Analytical Hierarchy Process (AHP). Multi-criteria decisions using AHP process have been used to solve problems in various fields such as control science, optimization, socio-economics, policy, strategy, planning etc. [18-19]. The use of hierarchical systems with complex estimation criteria has been presented clearly and firmly by Chou and Liang (2001) [20]. Furthermore, AHP analysis is also integrated to solve engineering problems such as linear programming, fuzzy logic etc. [21]. Therefore, many researchers have used fuzzy theory combined with AHP method to solve fuzzy comparison matrix to achieve the desired goal better [22].

In the Fuzzy-AHP method, instead of using precise numerical scales as in the traditional AHP, a fuzzy scale is applied to better capture the uncertainty and subjective perceptions of experts when comparing the relative importance of criteria. In this study, four main criteria and thirteen sub-criteria are considered to evaluate the implementation of the e-Navigation model in Vietnam. A fuzzy pairwise comparison matrix is constructed, in which experts compare each pair of criteria using triangular fuzzy numbers (TFNs). These TFNs, expressed as a triplet, represent the lower, modal, and upper bounds of the expert's judgment, thereby accommodating vagueness in linguistic assessments such as “equally important,” “moderately more important,” or “extremely more important.” The aggregated fuzzy judgments from all experts are then used to calculate fuzzy weights for each criterion. The process starts by finding a set of standardized weights by applying fuzzy aggregation and range analysis, and then these standardized weights are defuzzified using the weighting

Table 2. Linguistic responses and fuzzy scale transformation chart.

Linguistic scale	TFN scale	TFN reciprocal scale
Just equal	(1,1,1)	(1,1,1)
Equal importance	(1/2,1,3/2)	(2/3,1,2)
Weakly more important	(1,3/2,2)	(1/2,2/3,1)
Strongly more important	(3/2,2,5/2)	(2/5,1/2,2/3)
Very strongly more important	(2,5/2,3)	(1/3,2/5,1/2)
Absolutely more important	(5/2,3,7/2)	(2/7,1/3,2/5)

Source: [10], [23]

method to determine the priority weight values. The determined values represent the relative importance for each factor in the hierarchical model.

To reduce the impact of individual cognitive bias and improve the efficiency of the decision-making process, the AHP integration method with fuzzy logic is used. This integration is especially effective when decision-making for complex problems based on multi-criteria is based on a larger qualitative assessment. In the context of e-Navigation for Vietnam, the method ensures that the prioritization of criteria reflects both expert consensus and the inherent uncertainty in maritime operational environments.

Fuzzy numbers and fuzzy synthetic extent

Fuzzy set in this study is a continuous sequence of values running from 0 to 1. No member is represented by 0 and all members are represented by 1 [16]. Fuzzy number ɱ on R to be a triangular fuzzy number (TFN) with three points if its membership function of ɱ is equal to Eq. (1).

$$f\text{ɱ}(x)=\begin{cases}0, & x<l\\ \frac{x-l}{m-l}, & l\le x\le m\\ \frac{u-x}{u-m}, & m\le x\le u\\ 0, & x>u\end{cases} \quad (1)$$

Considering two triangular fuzzy numbers $\text{ɱ}_1=(l_1, m_1, u_1)$ and $\text{ɱ}_2=(l_2, m_2, u_2)$ that can be operated according to their laws as below:

Addition:

$$\text{ɱ}_1+\text{ɱ}_2=(l_1+l_2, m_1+m_2, u_1+u_2) \quad (2)$$

Subtraction:

$$\text{ɱ}_1-\text{ɱ}_2=(l_1-l_2, m_1-m_2, u_1-u_2) \quad (3)$$

Multiplication:

$$\text{ɱ}_1\times\text{ɱ}_2=(l_1\times l_2, m_1\times m_2, u_1\times u_2) \quad (4)$$

Division:

$$\text{ɱ}_1^{-1}=\left(\frac{1}{u_1},\frac{1}{m_1},\frac{1}{l_1}\right) \quad (5)$$

The linguistic values collected in the study by the fuzzy method were converted into fuzzy numbers as shown in Table 2.

Algorithm of fuzzy AHP

The steps of FAHP and the extent to FAHP is utilized, which were originally introduced by Chang as below.

Let $X=\{x_1, x_2, \ldots, x_n\}$ be a set of objects and $U=\{u_1, u_2, \ldots, u_n\}$ be a set of targets. To analyze each target, consider taking each object and performing the corresponding range analysis. Therefore, m range analysis values can be determined for each target corresponding to the following signs:

$$M_{g_1}^1, M_{g_2}^2 \ \ldots, M_{g_i}^j, i = 1,2,\ldots,n. \quad (6)$$

where, all the $M_{g_i}^j (j = 1, 2, \ldots, m)$ are triangular fuzzy numbers and g_i corresponds to the goal.

Step 1. The value of fuzzy synthetic extent with respect to the i^{th} object is defined as:

$$Si = \sum_{j=1}^m M_{g_i}^j \left[\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j\right]^{-1} \quad (7)$$

To obtain $\sum_{j=1}^m M_{g_i}^j$ perform the fuzzy addition operation of m extent analysis values for a particular matrix such as:

$$\sum_{j=1}^m M_{g_i}^j \left(\sum_{j=1}^m l_j, \sum_{j=1}^m m_j, \sum_{j=1}^m u_j\right) \quad (8)$$

In order to obtain $\left(\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j\right)^{-1}$ the fuzzy addition operation of $M_{g_i}^j$ ($j = 1, 2, \ldots, m$) value is performed as follows.

$$\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j = \left(\sum_{i=1}^n l_i, \sum_{i=1}^n m_i, \sum_{i=1}^n u_i\right) \quad (9)$$

And the inverse of the vector in Eq. (9) is computed as

$$\left[\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j\right]^{-1} = \left(\frac{1}{\sum_{i=1}^n u_i}, \frac{1}{\sum_{i=1}^n m_i}, \frac{1}{\sum_{i=1}^n l_i}\right) \quad (10)$$

Step 2. As M_1 and M_2 are two triangular fuzzy numbers, the degree of possibility of $M_1 = (l_1, m_1, u_1) \leqslant M_2 = (l_2, m_2, u_2)$ is defined as [17], [23].

$$V(M_1 \le M_2) = \sup_{x\le y}\left[\min\left(\mu_{\text{ɱ}_1}(x)\right), \left(\mu_{\text{ɱ}_2}(y)\right)\right] \quad (11)$$

$$V(M_1 \le M_2) = \mathrm{hgt}(M_1 \cap M_2)$$

$$= \mu_{M_2}(d) = \begin{cases}1, & if\ m_1 \le m_2\\ 0, & if\ l_1 \ge u_2\\ \frac{l_1-u_2}{(m_2-u_2)-(m_1-l_1)} & \text{otherwise,}\end{cases} \quad (12)$$

where, d is the ordinate of the highest intersection point between $\mu_{\text{ɱ}_1}$ and $\mu_{\text{ɱ}_2}$, and hgt is height. The numbers M_1 and M_2 should be compared calculating both, $V(M_1 \le M_2)$, and $V(M_1 \ge M_2)$ values.

Step 3. The degree possibility of a convex fuzzy number to be greater than k convex fuzzy M_i ($i = 1, 2 \ldots k$) numbers can be defined by:

$$V(M \ge M_1, M_2, \ldots, M_k)$$
$$= V\begin{bmatrix}(M \ge M_1) \text{ and } (M \ge M_2) \text{ and } \ldots \\ \text{and } (M \ge M_k)\end{bmatrix}$$
$$= \min V(M \ge M_i),\ i = 1,2,3,\ldots,k. \quad (13)$$

Assume that

$$d'(A_i) = \min V(S_i \ge S_k)$$
$$k = 1,2,\ldots,n; k \ne i \quad (14)$$

Then the weight vector is given by

$$W' = \left(d'(A_1), d'(A_2), \ldots, d'(A_n)\right)^T \quad (15)$$

where A_i ($i = 1, 2, \ldots, n$) are n elements.

Step 4. Via normalization, the normalized weight vectors are

$$W = \left(d(A_1), d(A_2), \ldots, d(A_n)\right)^T \quad (16)$$

where W is a non-fuzzy number.

Consistency Index (CI)

Table 3. Values of the Random Index (RI).

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

Saaty [18] has proposed a consistency index (CI), which is related to the eigenvalue method applied in the matrix, for which:

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{17}$$

where n is the dimension of the matrix and $\lambda_{\max}$ is maximal eigenvalue, work [18] suggested that if $CI/RI < 0.1$, the pairwise comparison matrix is characterized by an acceptable level of consistency. RI is a random index (the average CI of 500 randomly filled matrices), the values of which have been predefined by Saaty [18] for problems with $n \leq 10$ as indicated in the Table 3 below.

From the theoretical basis above, a pair-wise comparison tool is set up by using the Visual C# tool programming. In order to check the consistency of the matrix, it is required to calculate the consistency ratio:

CI = 0.01128, CR= 0,0835 < 0.10

It means that Fuzzy AHP sequencing result is of high consistency, the distribution of weight coefficient is very reasonable.

3. RESULTS AND DISCUSSION

In this study, we conducted questionnaires to “pool experts” as stake-holder groups to contribute in the development of Vietnam maritime field, consisting of individuals with expertise in the following areas: Vietnam Maritime and Inland Waterways Administration, Maritime Port Authorities, Vietnam Maritime Safety Corporation, Departments of Transport, Vietnam Coast Guard, Vietnam Customs, Vietnam Border Guard, Vietnam Fisheries Surveillance, Vietnam People’s Navy, the Maritime Search and Rescue Coordination Centre, Departments of Agriculture and Rural Development, the Institute of Marine Resources and Environment, seaport enterprises, and maritime telecommunications service providers who have at least over 5-year experiences. These experts are asked to compare four main criteria and 13 factors (Table 1) in the range of evaluation as the as well as the specific type of port in this study. The majority of participants agreed with the list of competent authorities provided, identifying the Vietnam Maritime and Inland Waterways Administration as the lead governmental body responsible for developing the strategic plan and overseeing the unified implementation of the e-Navigation model nationwide.

The calculated weights presented in Table 4 indicate that four primary criteria play a pivotal role in developing the e-Navigation model in Vietnam: Technological Infrastructure (0.320), Governance and Standardization (0.265), People and Processes (0.211), and Information and Data (0.204). Although the weight values of the criteria are different, they are closely related to each other, forming a tightly integrated framework that helps the e-Navigation system operate effectively.

Table 4. Detailing important factors for evaluation.

Upper level		Lower level	
C1	0,265	C11	0,116
		C12	0,093
		C13	0,082
C2	0,320	C21	0,051
		C22	0,101
		C23	0,101
C3	0,204	C31	0,056
		C32	0,038
		C33	0,049
		C34	0,047
		C35	0,034
C4	0,211	C41	0,162
		C42	0,070

Firstly, Technology Infrastructure has a weight of 0.320. This factor allows the provision of equipment systems and technical foundation materials of the e-Navigation system such as satellite systems, maritime equipment, data communication networks, information storage and processing centers. The ability to transmit, collect and process data in real time depends largely on the quality of the system's technology infrastructure. Investing in modern and synchronous infrastructure according to international and regional standards helps ensure the consistency, international integration, and high reliability of e-Navigation services in the context of the Vietnamese maritime industry developing strongly according to the strong marine economic development strategy of a coastal country like Vietnam.

Second, the Governance and Standardization factor has the highest weight of 0.265. This shows that the institutional framework and technical standards play a central role in the system. Good coordination between state management agencies on maritime, shipping enterprises, seaport enterprises, and related service providers determines the effectiveness of the system's governance. Moreover, fully implemented international standards of IMO, IALA, and ITU will ensure connectivity, interaction, and information security. It can be seen that this factor is an important measure of the level of integration of the Vietnamese maritime industry with the global maritime network.

Third, the Human and Process factor has a weight of 0.211, showing the important role of human resources in operating the system. An e-Navigation system with modern technology still requires highly competent operators who are ready to make optimal decisions. Those directly involved in operating the e-Navigation system such as deck officers, VTS officers, and management staff must be trained and updated on the operating procedures for using technological equipment systems, coordinating and using maritime data, especially incident response. Building and operating standardized procedures will bring high efficiency in state management, enhance maritime safety and improve the operational efficiency of the Vietnamese maritime industry.

Finally, the Information and Data element is considered the fuel of the e-Navigation system, achieving a weight of 0.204. Data with high accuracy, good quality, timeliness and security will determine the effectiveness of maritime management and maritime traffic. Therefore, Vietnam needs to build and develop a highly unified maritime database, integrate national and international maritime data sources, and have modern cybersecurity solutions to handle potential cyber threats.

In general, the four main factors are closely interrelated: the management and standardization factor are the basis for coordination, the technology infrastructure factor is the tool for implementation, the human factor and the process of using the tools to ensure system operation, and the information and data factor ensures that information and data are transparent, accurate and of high quality. The balanced and harmonious development of these main factors will have a great impact on the successful implementation of the e-Navigation model in Vietnam. This contributes to improving maritime safety, improving the operational efficiency of the Vietnamese maritime industry, towards sustainable development. Looking at Table 4, it also shows that when implementing the e-Navigation model in Vietnam, the level of influence of each factor is different. This shows the priority order of each factor in operating the system safely and effectively in accordance with the context of Vietnam. The User factor has a weight of 0.162, ranking first, showing that people are still the center of the system. Direct users are shore system operators, VTS officers, port operators, ship crew members and other stakeholders who will determine the system's performance. Not only the requirements for implementation capacity and technology level, but also the ability to coordinate and make decisions are especially important in ensuring maritime safety and preventing environmental pollution.

Next, the Governance factor (weighted at 0.116) will guide the system development strategy and allocate resources appropriately. It requires the state management agencies specializing in maritime, shipping companies, seaports, services and related parties to coordinate smoothly. Along with that, the Legal Framework (0.082) and Standardization (0.093) provide us with a suitable legal foundation, ensuring the ability to connect and interact between stations according to international standards of IMO, IALA, and ITU. The early development and improvement of legal regulations and technical standards of the Vietnamese e-Navigation system will help the Vietnamese maritime industry integrate into the global e-Navigation ecosystem. Regarding infrastructure factors, including Communication Infrastructure (0.101) and Onshore Infrastructure (0.101) ensure continuous and safe transmission, collection and processing of data, while Onboard Infrastructure (0.051) is prepared for operation, synchronized with shore systems to operate in real time throughout the system.

In terms of data, including factors such as Fast Data Exchange (0.049), Intuitive Data Presentation (0.047), Multi-Source Data Integration (0.038), Accurate Data Collection (0.056) and In-depth Data Analysis (0.034) are linked together into a complete process with high reliability and applicability in maritime operations. Finally, Transparent and consistent Operational Procedures (0.070) with smooth coordination will minimize errors and improve emergency response capacity.

In summary, these findings indicate that to successfully deploy e-Navigation in Vietnam, the core foundation is the key factors such as human factors, technology infrastructure, governance and data are harmoniously integrated. When researching investment in building an e-Navigation system according to priority weights of these factors, it will optimize resources, improve system performance and integrate into the international e-Navigation system soon.

4. CONCLUSION

This study aims to evaluate and prioritize the important factors affecting the implementation of the Vietnam e-Navigation model using the Fuzzy-AHP method. The findings show that there are 4 pillars that are closely related to each other and are the foundation for developing a safe, effective and sustainable system: Information and Data, Governance and Standardization, People and Processes, and Technology Infrastructure. Governance and Standardization are the most highly rated factors. This reflects the fact that institutional coordination, policy frameworks, and technical standards play an important role in directing the implementation. The most important human factor is user capacity. Users must be trained to exploit and operate in accordance with modern technology. This result clearly demonstrates the importance of human resource preparation and development, legally concretized strategic policy consistency, adequate infrastructure investment and robust, secure data management processes. When the system is smoothly integrated, the flow of high-quality, timely and secure data collected will support users in making real-time maritime decisions.

The results of this study provide maritime sector managers, policy makers and stakeholders with useful information based on systematic priority ranking of factors. Developing a Vietnamese e-Navigation system to improve safety, operational efficiency and environmental protection in line with these priorities will ensure Vietnam's successful integration into the global e-Navigation network.

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