

Original article

Evaluation of the Importance of Factors for Smart Port Transformation

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Abstract

This study aims to identify and prioritize the key factors essential for transforming a traditional port into a smart port using the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) based on Chang's extent analysis method. Based on the insights of 30 experts from Vietnam and South Korea, the research framework comprises three main dimensions, namely Policy, Operation, and Environment, which are further divided into ten sub-factors. The analysis revealed that Policy and Operation were perceived as the most critical dimensions, while Environment received relatively less emphasis. At the factor level, Automation & Intelligent Infrastructure ranked highest, followed by Investment & Financial Support, Productivity, and Regulatory Frameworks. In contrast, environmental factors such as Water & Waste Management and Emission Control were ranked lowest. Notably, Vietnamese and Korean experts all value the importance of advanced technology and investment capacity but still have some differences in prioritizing the other factors, reflecting differing national contexts and developmental stages. These findings offer strategic guidance for policymakers and port authorities in tailoring smart port development strategies to local conditions and priorities.

Keywords: Smart port, Fuzzy AHP, Sustainable development, Port transformation

1. Introduction

Ports have long been the backbone of international trade and global logistics, with around 80-90% of the world's merchandise being transported by sea (UNCTAD, 2023) (OECD, 2022). They have evolved into critical drivers of regional economic development and global trade, functioning not only as centers for transportation and logistics but also as strategic assets that enhance regions' and countries' ability to participate in international economic competition (Wang, et al., 2020). However, traditional port operations face many problems, such as complicated procedures and inefficient decision-making, which often cause port congestion (Xu, et al., 2024). Besides, the environmental effects of port activities are becoming more serious concerns. As a major source of greenhouse gases, the shipping industry is under growing pressure to lower its environmental impact without reducing its efficiency (Wang, et al., 2020).

Applying digitalization and automation has become a growing trend. It is necessary for a port to modernize so as to compete with other ports in the region as well as in the world. The top global ports, such as Shanghai, Singapore, and Rotterdam, are all equipped with maritime port information systems. For instance, Automated Yard System, Terminal Operating System, Port Community System, which allow these ports to reduce waiting times and streamline cargo flows, improve space utilization and container movement, make port infrastructure more efficient and optimize terminal operations (Juliana, et al., 2024). These challenges have led to the concept of the "smart port", a modern and technologically advanced port that leverages smart infrastructure and automation to optimize performance, sustainability, and meet the increasing demands of global trade.

The development of smart ports is a key aspect of transforming the maritime sector to enhance operational efficiency, reduce environmental impact, and improve competitiveness. A smart port incorporates advanced technologies such as sensors, automation systems, and artificial intelligence to improve port operations and decision-making processes (Xu, et al., 2024). Emission from ships can also be reduced by using greener infrastructure and technologies that shorten ship waiting times at berths, where air emissions during berthing are largely produced, mainly from auxiliary engines used for loading and unloading (Nguyen, et al., 2022), nearly ten

times higher than those from regular port operations (Gao, et al., 2025). The high concentration of pollutants in and around port areas not only contributes to global climate change but also poses serious health risks to nearby communities. Therefore, emission control and environmental sustainability are critical components in the transition toward smart port development.

On the other hand, the transformation from conventional ports to smart ports is a complex and multi-dimensional process that requires a careful evaluation of several strategic, technological, operational, and environmental factors. To navigate this complexity, several studies in maritime logistics, port management, and transportation systems have adopted Fuzzy Analytic Hierarchy Process (FAHP) to evaluate sustainability, port efficiency, emissions reduction, and other critical aspects of smart port development. FAHP allows for a systematic comparison of these factors and assigns relative importance to them, even when precise data is lacking or when experts may have differing opinions. This study leverages FAHP to address uncertainty in expert judgments, using linguistic terms converted into fuzzy numbers to ensure more reliable and accurate prioritization.

The motivation for this research stems from the need to develop sustainable, efficient, and resilient ports. While much of the existing literature focuses on technology and environmental aspects, there is a notable gap in studies that include the critical policy dimension, which is essential for effective smart port development. This study aims to fill this gap by identifying the key factors that influence smart port transformation.

By applying FAHP, this research aims to provide valuable insights for policymakers, port authorities, and stakeholders involved in port development, supporting better decision-making and strategic planning. Ultimately, the findings will help guide the transition to smart ports, ensuring alignment with both technological advancements and regulatory frameworks.

This paper is structured as follows: first, a literature review of the smart port concept and its key indicators is presented in Section 2. Then, Section 3 introduces the application of FAHP methodologies in evaluating port performance and transformation, followed by the results and discussion of Section 4. Finally, Section 5 concludes with strategic recommendations, limitations, and future

research directions.

2. Literature Review

This research aims to identify key factors necessary for transforming a port into a smart port. The literature review has three parts. The first part provides an overview of the smart port concept. The second part examines the key factors that should be considered in this transformation. Finally, the third section reviews the use of Fuzzy AHP to consider experts' weights on each aspect or indicator.

2.1. Smart Port Concept

The port sector plays a crucial role in today's economy, serving as key nodes that facilitate the movement of goods and raw materials across markets in the world. Even small improvements in profitability will have significant impacts due to the high volume of operations (González, et al., 2020). As trade volumes continue to rise, ports are also evolving to integrate smart technologies and sustainable practices to enhance efficiency and reduce environmental impact. This has led to widespread interest in the concept of "smart ports" across the industry (Othman, et al., 2022). Transforming into a smart port is indeed a prevailing trend within the global maritime industry.

The concept of smart port began gaining prominence in the 2010s (Molavi, et al., 2020) (Juliana, et al., 2024) as ports worldwide started integrating advanced technologies to enhance efficiency and sustainability (de la Peña Zarzuelo, et al., 2020), leading to extensive research on smart port definition and key indicators. However, there is no official and globally unified definition for smart port to date.

Various scholars and industry reports define smart ports in different ways. According to A. Rajabi et al., (2018), a smart port adopts advanced technologies such as IoT, cloud computing, robotics, and big data analytics to enhance efficiency and address past challenges (Rajabi, et al., 2018) (Lin, et al., 2022) (Yau, et al., 2020) (Juliana, et al., 2024). Similarly, B (Juliana, et al., 2024) defines a smart port as a port that incorporates automation, high productivity, and environmentally friendly services. It uses advanced and eco-friendly technologies to boost efficiency and enhance competitiveness. A smart port allows fast, safe, and cost-effective cargo delivery while relying on smart infrastructure and skilled personnel to achieve sustainability and optimize operations (Juliana, et al., 2024). Its development not only optimizes technology but also promotes social education, environmental protection, and energy efficiency to create an efficient, secure, and sustainable port (Lin, et al., 2022).

Moreover, a smart port should include five key aspects: smart infrastructure, well-educated personnel, automation, skilled workers, and environmental awareness (Chen, et al., 2019) (Molavi, et al., 2020).

The above literature review shows that a smart port can be considered a modern sea port that uses technologies such as automation, IoT, and well-trained personnel to operate it, and green solutions to improve efficiency, reduce environmental impact, and support sustainable development while optimizing operations.

In the existing smart port research, the literature is categorized into three main areas: the application and impact of digital transformation technologies, the evaluation of smart port performance, and the challenges and obstacles associated with smart port development (Pham, 2023).

Thanks to its benefits, the smart port concept is becoming a growing trend in the industry today. By adopting advanced technologies such as AI and automated facilities, smart ports can increase productivity and create a safer working environment for port workers by minimizing human involvement in dangerous tasks (Yau, et al., 2020). For instance, in crane operations, compared to traditional cranes, which require three operators working 24/7, leading to worker fatigue and increased labor costs, automation significantly reduces labor costs, as one operator can remotely manage three to six cranes from a distance via video surveillance (Al-Fatlawi & Motlak, 2023). Moreover, automation improves operational safety by minimizing human involvement. This shift to smart cranes enhances port productivity and reduces the risk of human errors. Or the application of an IoT-based ship berthing system helps reduce berthing and unberthing time by minimizing the requirement for manual berthing procedures, thereby contributing to smoother port operations and lowering costs (Kamolov & Park, 2019). Additionally, by using environmentally friendly energy, smart ports can reduce greenhouse gas emissions and environmental footprint to enhance environmental sustainability, an urgent issue over the past decade and that will continue in the coming years (Yau, et al., 2020).

Despite the huge advantages, the path to becoming a smart port is not without its challenges. These include insufficient government support in R&D, limited collaboration between port business and governmental authorities, a lack of professional manpower, and limited investment resources. Furthermore, a thorough understanding of related technologies is also required (Jia & Cui, 2021). Many modern ports in the world, such as Le Havre (France), Rotterdam (Netherlands), and Hamburg (Germany), have deployed smart ports

projects and applications (Yau, et al., 2020). While some other ports recognize the necessity of digital transformation and smart ports and are actively developing and implementing relevant policies and strategies, many lack sufficient readiness for the transition to smart ports (PAT, 2023). Therefore, for a port to become smart and sustainable in the long term, the transition process must be structured with pragmatic and actionable goals.

2.2. Smart port indicators

Several previous studies have built a framework to evaluate smart port performance. Based on previous research collected, Table 1 summarizes seven major aspects of smart ports: operation, energy, environment, cooperation, human factor, intelligence, and liberalization. The table has a total of 26 indicators for 7 dimensions. The table shows that the most commonly used dimensions to evaluate the performance of a smart port are operations, energy, environment, and intelligent infrastructure.

Meanwhile, (González, et al., 2020) rank Spanish Port System by developed smart port indicators categorized to 4 pillars: Operational Economic, Social, Political & Institutional and Environmental. ESCAP (United Nations Economic and Social Commission for Asia and the Pacific) provides a framework for assessing a port's (in Southeast Asia) readiness and performance in adopting smart technologies. There are six dimensions: management, financial and investment, human capital, functionality, innovation level, technology system/tools (PAT, 2023). Additionally, (Lin, et al., 2022) investigates the impact of different port governance on the development strategies of smart ports by establishing 5 evaluation main criteria: operational economics, environmental protection, energy sustainability, maritime safety and community service.

Most existing studies on smart port development have focused on technological, operational, environmental, and economic aspects. In contrast, policy has rarely been treated as an independent dimension; when it is mentioned, it is often limited to areas such as trade policy, investment openness, or workforce development. These studies tend to overlook the active and strategic role of policy in enabling smart port transformation. In contrast, this study conceptualizes policy as a dynamic enabler that drives innovation, fosters cross-sector collaboration, secures financial investment, and ensures workforce adaptability. The key distinction of this study lies in its development of a comprehensive set of evaluation criteria that not only integrates indicators from previous studies, but also explicitly incorporates

policy as a distinct dimension and presents the prioritization of its relative importance for practical policy development. Consequently, the outcome of this study will provide a clearer understanding of the critical factors and dimensions that influence the successful transformation of ports into smart ports. The results will not only highlight the most critical areas to focus on but also help shape more effective strategies for port development, ensuring that these transitions are sustainable.

2.3. Fuzzy Analytic Hierarchy Process (FAHP)

Today, many studies rely on expert opinions to evaluate and rank the relative importance of various service quality factors. This approach has become a common method for assessing key performance indicators in various industries, including the maritime logistics industry. (Yen, et al., 2023) used AHP method to examine the impact of smart port design and three dimensions automation, environment, and intelligence are identified. (Hsu, et al., 2022) Identified key success factors for smart ports include accurate cargo delivery, seamless electronic document transfer, quick berth availability, efficient logistics and customs processes, transparent information integration, and effective use of big data by incorporating AHP and DEMATEL. Compared to traditional AHP method, FAHP offers advantages in handling uncertainty and imprecision in expert judgments by incorporating fuzzy logic (Yan, et al., 2020). Ref (Othman, et al., 2020) implement the FAHP technique to identify key factors causing these imbalances at large-scale minor ports. Ref (Yang & Hsieh, 2024) also utilize FAHP to assist port operators and shipping companies in recognizing essential elements for successful digital transformation to enhance operational efficiency and address climate change challenges. For this study, smart port indicators are the factors that require FAHP to determine their relative weights.

3. Methodology

This study used the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) to identify and prioritize key factors for transforming a port into a smart port. While the traditional AHP method, developed by Saaty (1970s), relies on clear and consistent judgments from decision-makers, this is difficult to achieve due to the inherent subjectivity and ambiguity in human judgment. People don't always make decisions in a perfectly logical or consistent way, especially when dealing with complex topics.

To better reflect this reality, the study applied an extended version of Fuzzy AHP using Chang's extent analysis method (1996), which uses triangular fuzzy

(16 experts) having more than 10 years of job tenure and 43.33% (13 experts) coming from academia or research institutes. In addition, the majority of respondents are in their 30s (40%) and 20s (36.67%),

indicating both experience and active involvement in the industry. This diverse and qualified composition enhances the reliability and validity of the research findings.

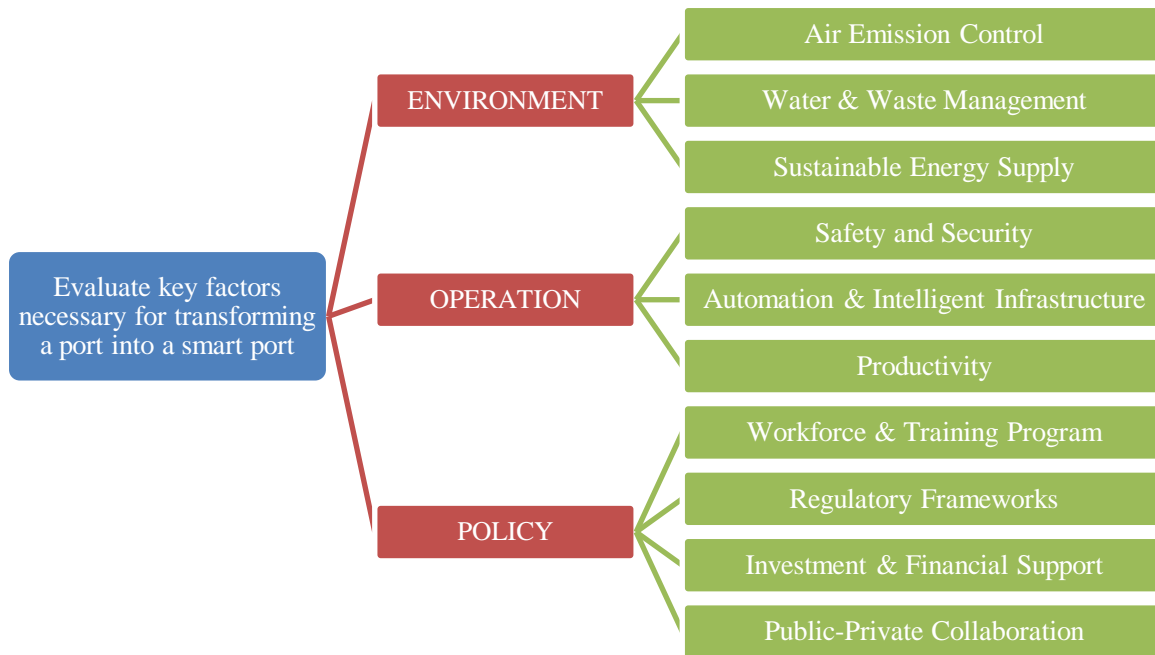


Figure 1: Hierarchical structure Fuzzy AHP analysis diagram for identifying key factors necessary for transforming a port in a smart port in the final analysis

Table 2: Composing of the Expert Panel on the Participation in the FAHP Survey

Variables	Item	Frequency	Percentage (%)	Variables	Item	Frequency	Percentage (%)
Job Tenure	< 5 years	11	10.00%	Occupation	Academia/Research institute	13	43.33%
	5~10 years	9	23.33%		Container/Terminal operator	2	6.67%
	11~15 years	4	6.67%		Other	8	26.67%
	16~20 years	3	3.33%		Public servant	4	13.33%
	> 20 years	3	20.00%		Shipping company/Shipper	2	6.67%
Age group	20s	11	36.67%		Captain	1	3.33%
	30s	12	40.00%		Job Title	Department Head/Team Leader	2
	40s	6	20.00%	Manager		2	6.67%
	50s	1	3.33%	Assistant Manager		2	6.67%
N = 30		100%		Staff		11	36.67%
				Lecturer		7	23.33%
				Other		6	20.00%
				N = 30		100%	

Table 3: Description of Main Criteria

Dimension	Description
Environment	Focusing on sustainability by reducing air emissions, managing water and waste, minimizing noise pollution, and optimizing energy use to protect ecosystems and communities.
Operation	Managing activities to maximize efficiency, safety, and effectiveness. It includes implementing safety protocols, integrating advanced technologies for streamlined processes, and monitoring productivity to optimize resource use and performance.

Policy Regulations and guidelines established by governmental and regulatory bodies to govern the operational, environmental, and collaborative aspects of port development. These policies are designed to ensure compliance, promote sustainability, enhance operational efficiency, and facilitate stakeholder engagement within the smart port ecosystem.

Table 4: Description of Sub Criteria

Dimension	Factor	Description
Environment	Air Emission Control	<p>Strategies and technologies used to reduce air pollution caused by port operations, including emissions from ships, cargo handling equipment, and transportation activities.</p> <p>Example: Reducing CO₂, SO₂, PM, HC, CO, NO_x can adopt Shore Power Systems, or electric cranes, etc.</p>
	Water & Waste management	<p>Strategies to ensure efficient water use, pollution prevention, sustainable marine ecosystem protection, as well as the efficient collection, treatment, recycling, and disposal of waste from port operations and vessels, ensuring environmental sustainability and regulatory compliance.</p> <p>Example: Ballast Water Treatment, Water Recycling Systems, Wastewater Treatment, Oil and fuel spill response.</p>
	Sustainable Energy Supply	<p>The adoption and integration of environmentally friendly energy sources, shore power for vessels, and energy-efficient technologies. Aiming to reduce carbon emissions, lower operational costs, and enhance energy security, while ensuring a reliable and sustainable power supply for port operations.</p> <p>Example: Installing solar panels on warehouses, LNG fuel supply stations.</p>
Operation	Safety and Security	<p>Port's use of regulations, standards, employee training, risk assessment, and/or monitoring systems to detect safety issues. This also involves close ship-to-shore coordination to ensure prompt emergency response, pollution control, and risk mitigation efforts that protect both workers and the environment.</p> <p>Example: Real-Time Surveillance, Access Control System, Integrated safety protocols.</p>
	Automation & Intelligent Infrastructure	<p>The integration of AI, robotics, IoT, and smart systems to optimize operations. It enhances efficiency, safety, and sustainability by automating tasks, utilizing real-time data, and enabling intelligent decision-making with minimal human intervention, including synchronized ship-to-shore operations that minimize berth time and reduce emissions.</p> <p>Example: Digital Twin, 5G, Automated Crane, AGVs, Automated Berth Assignment Systems.</p>
	Productivity	<p>The extent to which the port operations are carried out efficiently within the limits of time, budget, space, and available facilities. Coordinated planning between ships and terminals that aligns estimated time of arrival with berth and crane readiness enhances cargo handling speed, reduces turnaround time, and improves space utilization.</p> <p>Example: Berth productivity, Infrastructure productivity.</p>

Policy	Investment & Financial Support	Funding, financial policies, and incentives that enable the development of smart port infrastructure and operations. It includes both public and private sector investments such as government funding, private investment, and tax incentives. Example: Government Grants And Subsidies, Private Investment, Tax Incentives.
	Regulatory Frameworks	Set of rules, laws, and industry standards that ports must follow to ensure safety, security, efficiency, and sustainability. Example: International Maritime Laws (IMO, ISPS Code,...), Pollution Control (MARPOL Annex VI,...)
	Workforce & Training Program	Strategies and regulations that ensure the development, reskilling, and training of port workers to adapt to automation, digital transformation, and new operational technologies. Example: Training Programs, Ensuring a safe work environment.
	Public-Private Collaboration	The level of cooperation between government agencies, private enterprises, and industry stakeholders to drive smart port innovation, investment, and operational efficiency. Example: Research And Development Partnerships, Joint Infrastructure Projects.

3.3. FAHP Calculation Process

To provide a clear overview of the research process, a flowchart is presented in Figure 2. It outlines the main steps of the FAHP method used in this study, from defining the hierarchy and collecting data to the calculation of fuzzy weights and prioritization of key factors.

Each element in the pairwise comparison matrix is expressed as a triangular fuzzy number (TFN) which is defined by a triplet: $\tilde{A} = (l, m, u)$ where l, m, u are the lower, most likely, and upper bounds. These fuzzy numbers correspond to linguistic terms that capture the relative importance of one criterion over another. Table 5 presents the fuzzy scale, and its reciprocal values used in this study for assessing the significance intensity between criteria.

For each criterion i , the synthetic extent S_i is computed by using Eq. (1):

$$S_i = \frac{\sum_{j=1}^n \tilde{M}_{ij}}{\sum_{i=1}^n \sum_{j=1}^n \tilde{M}_{ij}} \quad (1)$$

Where:

- \tilde{M}_{ij} is the fuzzy comparison value for criterion i against j
- The division of fuzzy numbers involves fuzzy arithmetic (inverse and multiplication)

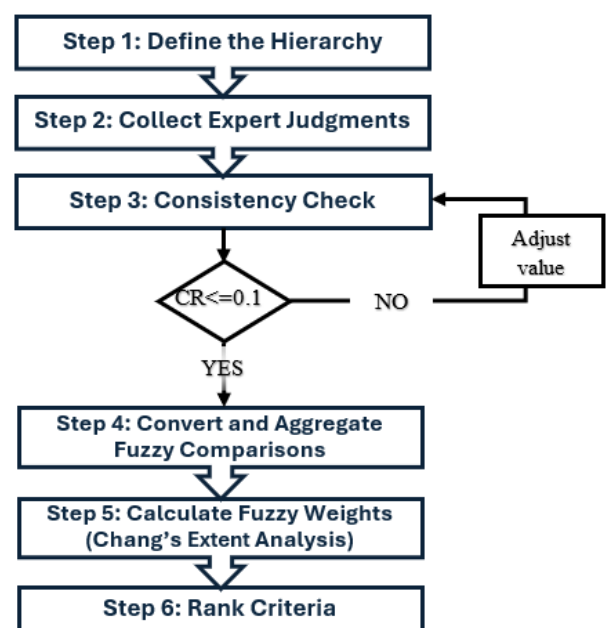


Figure 2: Flow chart of the methodological approach presented in the study

To compare the relative importance of criteria, the degree of possibility between fuzzy numbers was calculated as follows. The degree of possibility that fuzzy number $\tilde{A}_1 = (l_1, m_1, u_1)$ is greater than $\tilde{A}_2 = (l_2, m_2, u_2)$ is given by Eq. (2):

$$V(\tilde{A}_1 \geq \tilde{A}_2) = \begin{cases} 1, & \text{if } m_1 \geq m_2 \\ 0, & \text{if } l_2 \geq u_1 \\ \frac{l_2 - u_1}{(m_1 - u_1) - (m_2 - l_2)}, & \text{otherwise} \end{cases} \quad (2)$$

This value helps compare fuzzy synthetic extents across criteria.

To get crisp weights from the fuzzy synthetic extents, compute the degree of possibility for each S_i compared to others.

Then: $d_i = \min V(S_i \geq S_j), \text{ for all } j \neq i$

Finally, normalize these values: $w_i = \frac{d_i}{\sum_{i=1}^n d_i}$ (3)

This gives the final weight vector w , which represents the priority of each criterion.

Table 5: Description of TFN scale for significance intensity

Relative importance	Linguistic terms	Fuzzy scale	Fuzzy reciprocal scale
1	Equal importance	(1,1,1)	(1,1,1)
3	Moderately more important	(2,3,4)	(1/4,1/3,1/2)
5	Strongly more important	(4,5,6)	(1/6,1/5,1/4)
7	Very strongly more important	(6,7,7)	(1/7,1/7,1/6)

4. Result and discussion

This study aimed to identify and prioritize the key factors essential for transforming a port into a smart port, utilizing the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) based on Chang’s extent analysis

method. Through expert input and systematic analysis, the research established three main criteria and ten sub-factors. The findings offer strategic guidance for sustainable development and smarter transformation of ports.

The methodology used in this study was Fuzzy AHP. Traditional AHP developed by Saaty (1970s) requires clear judgment from decision makers. However, due to the complexity and uncertainty of real-world decision-making, individuals often provide ambiguous judgments. In this study, the extended Fuzzy AHP method based on Chang’s (1996) triangular fuzzy scale was employed as the research methodology, chosen for its computational simplicity and ease of implementation in Excel.

To assess the reliability of the expert judgments, the Consistency Ratio was calculated for each of the 30 pairwise comparison matrices. According to Saaty (1980), a consistency ratio value of less than 0.1 indicates acceptable consistency. In this study, all 30 experts had consistency ratio values below this threshold, confirming the logical consistency of their responses.

The analysis revealed that among the main-level criteria, Policy was the most important factor (0.4558), followed by Operation with just a little bit less weight (0.4404), and Environment (0.1038). This indicates that Policy and Operation are perceived as the foundation for successful smart port transformation. Among the three dimensions, environmental factors were considered the least important.

Table 6 presents the weights and rankings of 10 evaluation factors for smart port development. It includes local and global weights, along with the overall global weights and ranks.

As per the outcomes depicted in Table 6, Automation

Table 6: The weights of Smart Ports Evaluation Factors

Dimensions	Weights	Factors	Overall Local Weights	Overall Global Weights	Rank
Environment	0.1038	Emission Control	0.2380	0.0247	9
		Water & Waste Management	0.0108	0.0011	10
		Sustainable Energy Supply	0.7512	0.0780	8
Operation	0.4404	Safety & Security	0.1933	0.0851	7
		Automation & Intelligent Infrastructure	0.5145	0.2266	1
		Productivity	0.2922	0.1287	3
Policy	0.4558	Investment & Financial Support	0.3271	0.1491	2
		Regulatory Frameworks	0.2819	0.1285	4
		Workforce & Training Program	0.1979	0.0902	5
		Public-Private Collaboration	0.1932	0.0881	6

& Intelligent Infrastructure (0.2266, Rank 1) and Productivity (0.1491, Rank 3) collectively dominate the global weights, underscoring ports' urgent focus on efficiency and technological adoption. The prioritization of Automation and Intelligent Infrastructure reflects growing consensus among experts and stakeholders that intelligent technologies are not merely supportive tools but critical enablers of sustainable, efficient, and competitive port operations. This rank also was agreed with the previous study of G.Buiza et al., (2016) (Yen, et al., 2023). This aligns with global trends where automation and digitalization are shown to drastically improve efficiency and safety. At the Putian terminal, automation improved efficiency by reducing vehicle turnaround by 127 minutes through optimized scheduling and intelligent systems (UNCTAD, 2021). Unlike manual inspections or time-consuming simulations (30 seconds per check), AI can deliver results in just 0.015 seconds with 99.999% accuracy and help avoid costly disruptions like the \$21 million incident in Taiwan (Jayasinghe, et al., 2024).

Intelligent infrastructures such as automated cranes, smart yard systems, IoT-based tracking, and digital

significant capital investment toward digitizing operations, upgrading legacy systems, and implementing smart infrastructure (e.g., automated cranes, digital twins, IoT systems). Automation isn't just a "cost", it's a strategic asset that unlocks efficiency, attracts funding, and reduces long-term operational expenses.

The high rank of Investment & Financial Support (0.1491, rank 2) confirms that financial capability is the most important enabler under the policy dimension. Technologies such as digital twin systems, autonomous vehicles, or AI-based maintenance require significant upfront and continuous capital. Therefore, there will be a growing need for Public-Private Partnership frameworks and joint ventures between port authorities, technology providers, and cargo owners to support digital transformation projects and integrate green infrastructure.

Both Korean and Vietnamese experts ranked "Investment & Financial Support" and "Automation & Intelligent Infrastructure" among the top two highest priorities, which are illustrated in Table 7, indicating a shared recognition of the critical role financial

Table 7: Comparison of Factor Priorities by Korean and Vietnamese Experts

Dimensions	Factors	Korean experts			Vietnamese experts		
		Main Criteria Weights	Global Weights	Rank	Main Criteria Weights	Global Weights	Rank
Environment	Emission Control		0.0765	7		0.0030	9
	Water & Waste Management	0.2177	0.0000	10	0.0213	0.0021	10
	Sustainable Energy Supply		0.1412	3		0.0161	8
Operation	Safety & Security		0.0765	6		0.0909	7
	Automation & Intelligent Infrastructure	0.3661	0.1494	2	0.4944	0.2998	1
	Productivity		0.1402	4		0.1037	5
Policy	Investment & Financial Support		0.2058	1		0.1311	2
	Regulatory Frameworks	0.4161	0.1327	5	0.4844	0.1309	3
	Workforce & Training Program		0.0147	9		0.1206	4
	Public-Private Collaboration		0.0630	8		0.1017	6

twin models help to increase annual throughput capacity, productivity also grows while reducing the number of required workers and operating expenses (Chen, et al., 2020). Additionally, smart digital solutions that minimize the use of paper can help mitigate climate change (UNCTAD, 2021).

This means port authorities should prioritize automated and digital infrastructure investments even before expanding green initiatives or policy reforms. Ranking automation as the top priority implies that port authorities and governments must allocate

resources and technological advancement play in port transformation.

The prioritization of productivity (rank 3) reflects ports' immediate need to compete globally, but without parallel investments in sustainability and workforce development, these gains may prove unsustainable long-term. The study empirically confirms that improving loading/unloading productivity directly reduces emissions per TEU (Nguyen, et al., 2022), validating the high ranking of Productivity (Rank 3) and Automation & Intelligent

Infrastructure (Rank 1) within the Operation dimension, which highlights the critical role of operational efficiency in achieving both economic and environmental sustainability.

Safety & Security (Ranking 7th) highlights that ports must ensure operational safety in parallel with automation and green innovation.

Regulatory Frameworks (0.1285, Rank 4) imply that a strong regulatory framework sets the rules that make smart port development possible. A well-designed regulatory framework accelerates smart port transformation by creating the legal Infrastructure for Digital Innovation, and collaborative conditions necessary for investment and sustainable growth. Without it, even the most advanced technologies can stall due to uncertainty, risk, or lack of coordination. The European Union's Alternative Fuels Infrastructure Regulation (AFIR) set clear requirements for reducing port-related emissions, which in turn encouraged the Port of Rotterdam to plan 8 to 10 shore power projects targeting different vessel types to address air pollution and noise nuisance (Anon., 2020).

The relatively lower weights of Public-Private Collaboration (0.081) and Workforce & Training Program (0.09021) suggest that stakeholders may perceive these factors as supportive enablers rather than direct drivers of smart port transformation. However, these factors remain valuable. For instance, the collaboration between Huawei Technologies Co., Ltd. and the Port Authority of Thailand highlights the importance of public-private partnerships to implementing 5G, green port solutions, and enhancing digital skills among port personnel (Anon., 2022). While the collaboration between the Port Authority of Thailand and Huawei is still at the early stages of development, a more mature case can be seen in Tianjin Port, China, where Huawei's collaboration with local authorities led to a 60% reduction in staffing needs, a 30% decrease in overall costs, and a 17% reduction in energy consumption at Tianjin Port (Anon., n.d.). These results highlight how public-private efforts can serve as a catalyst for technological integration, supporting the argument that such partnerships are a critical enabler of smart port success.

Compared to Operation and Policy, the Environment dimension just weighs 0.1038, much lighter than the two others, which also lowers the relative importance of the three factors under this dimension. It reflects perception that environmental practices are outcomes of transformation, not the drivers. The lowest-ranked factors group includes Sustainable Energy Supply (0.0780), Emission Control (0.0247) and Water &

Waste Management (0.0011). These factors, while still important, are currently viewed as supporting enablers rather than primary drivers of transforming into smart port. It can be seen as a sustainability trend, but not the top driver yet.

Aspects like safety and security, sustainable energy supply, emission control, and waste resource management are seen as necessary but not yet prioritized. However, overlooking these could create bottlenecks in implementation, and long-term sustainability if not addressed in parallel. Ports focus first on digital and operational improvements, then green solutions follow.

However, there are also some noticeable differences. Korean experts gave more weight to environmental aspects, such as sustainable energy supply (rank 3 vs rank 8 in Vietnam) compared to Vietnamese experts. On the other hand, Vietnamese experts placed higher importance on workforce and training programs (rank 4), which were ranked much lower (rank 9) by Korean experts, suggesting that human resource development is seen as more urgent in Vietnam.

The differences observed can be attributed to the maturity level of each port and the broader national context. Busan Port, one of the busiest ports globally, has already achieved a high degree of automation (MOF, 2023). At this advanced stage, the focus shifts towards supportive investments aimed at fostering further innovation and enhancing resilience. To maintain competitiveness with other global ports and regions such as Europe, where environmental concerns are crucial, Busan must continue accelerating its digital transformation and sustainable initiatives. As a member of the OECD, Korean port authorities also prioritize policies aligned with international standards.

Regarding the relatively low ranking of Emission Control, despite its recognized importance, Korea has implemented significant measures such as the Carbon Neutrality Act (2021) (Korea, 2024) and the establishment of its own K-Emission Trading System (Anon., 2015). These proactive steps may explain why Emission Control ranks eighth, while investments in greener energy infrastructure are viewed more as a long-term strategic priority.

In contrast, Vietnam, as a developing country, is still in the early stages of port digitization. Vietnamese ports primarily focus on foundational development and have yet to achieve full automation (ESCAP, 2024). This reflects a broader trend in developing nations, where economic growth and infrastructure development take precedence, with environmental

sustainability emerging as a priority at a later stage. Consequently, Vietnamese experts tend to give environmental factors lower in importance. Automation is thus seen as the most effective means to enhance port performance, reduce labor inefficiencies, and keep pace with increasing trade volumes. Additionally, while Vietnam's seaport workforce is improving, challenges remain in education, technology adoption, and consistent training to meet global smart port standards, which explains why workforce development ranks relatively higher compared to Korea.

5. Conclusion

The purpose of this study is to identify the priorities of factors that can transform a traditional port into a smart port. To achieve this, the study reviewed previous literature and selected suitable works to build a hierarchical framework. Additionally, a new dimension, Policy was introduced to reflect its growing importance in smart port development. The research conducted a survey with 30 experts from Vietnam and Korea to collect their opinions. The Fuzzy AHP method, based on Chang's Extent Analysis, was then applied to determine the relative weights of the smart port indicators.

There are two main contributions of this study to existing literature. Firstly, it emphasizes the critical role of Policy as a new dimension in smart port development. Secondly, the results showed that Policy and Operation are the most critical dimensions. At the factor level, Automation & Intelligent Infrastructure, Investment & Financial Support, Productivity and Regulatory Framework ranked highest, highlighting the growing importance of technology integration, operational efficiency and other policy index in driving into the smart port.

Despite providing valuable insights, this study has several limitations. The expert sample consisted of 20 Vietnamese and 10 Korean participants with diverse occupations and experience levels. During the survey process, efforts were made to gather a wide range of opinions from port operation practitioners, government officials, and academic experts in both Korea and Vietnam. However, a limitation of the study is that approximately half of the respondents were affiliated with academic or research institutions. Nevertheless, these respondents had conducted port-related research for several years, which suggests a high level of understanding regarding the transformation toward smart ports. Additionally, 16 out of 20 Vietnamese experts (80%) had more than five years of professional experience, whereas only 30% of the Korean experts met this threshold. This

imbalance in experience may have influenced the consistency of the findings and is considered a limitation to be addressed in future studies. Nevertheless, detailed explanations regarding the study's purpose, the hierarchical structure, and the evaluation criteria were provided to participants during the survey process to enhance the accuracy and reliability of their responses. Future research could expand the sample size, incorporate additional stakeholder perspectives, or apply other decision-making methods for cross-validation.

Although the ranking appears intuitive with operational factors leading, the expert-based FAHP process quantifies and validates these assumptions within the specific context of container terminals. The results also help identify which sub-factors deserve immediate versus future focus, providing a structured foundation for phased implementation.

These findings carry important implications for policymakers. Prioritizing supportive regulatory frameworks and strategic investments, while fostering technological innovation and operational improvements, appears essential for a successful smart port transition. Although environmental concerns ranked lower, their integration should not be overlooked, particularly in the broader context of global sustainability goals.

Acknowledgement

This research was supported by National University Development Project through the National Research Foundation of Korea funded by the Ministry of Education.

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Received **10 June 2025**

1st Revised **02 July 2025**

Accepted **05 July 2025**