An Empirical Study for Transforming Egyptian Seaports into Smart Ports Through Suggesting a Strategic Roadmap

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Abstract

Purpose: *This study aims to develop a structured roadmap for transforming Egyptian seaports into smart ports by aligning with international standards to enhance operational efficiency, sustainability, and global competitiveness.*

Design/methodology/approach: *Using a quantitative research methodology, the study conducts an extensive literature review to identify critical pillars of smart port readiness, including digitalization, operational efficiency, safety and security, sustainability, cybersecurity, and human resources. Primary data was gathered through online surveys distributed to port managers and maritime industry experts to assess the current state of Egyptian ports.*

Findings: *The study identifies several gaps in the current infrastructure and practices of Egyptian ports, notably in automation, digital integration, and cybersecurity. Based on empirical data, it proposes a phased roadmap to smart port development focusing on strategic improvements in digitalization, automation, sustainability, and workforce capabilities.*

Research implications: *This research provides a theoretical framework for assessing smart port readiness; however, its scope is limited to quantitative methods and the specific context of Egyptian ports. Broader generalizability may require comparative studies across different regions or the inclusion of qualitative data.*

Practical implications: *The roadmap offers actionable insights for policymakers, port authorities, and stakeholders seeking to enhance port operations through smart technologies. It supports the design of phased interventions to address existing gaps and ensure a sustainable transformation.*

Originality: *This study contributes a context-specific, data-driven roadmap tailored to the unique needs of Egyptian ports. It fills a gap in the literature that predominantly focuses on ports in more developed economies. It offers a replicable framework for other developing countries aiming for smart port transformation.*

Keywords: *Smart ports, digital transformation, automation, cybersecurity, sustainability, Egyptian ports.*

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Introduction:

A port is both a platform and a node in the worldwide maritime transportation network, as well as a driver of global economic and trade growth (Lee *et al*., 2016). Because the port system is such an essential part of the global economic system, the primary incentive for port development is a combination of industrial evolution, market systems, and port competition (Gonzalez *et al*., 2020).

All facets of social and economic life are being impacted by the ongoing digitalization that is currently taking place throughout the world. Despite this, economies and cultures have changed in a variety of ways over time. Technology has been daringly expanding into new fields (Karas, 2020), which will undoubtedly influence the quality of port service shortly. Simultaneously, several port environments, such as port administrations, terminals, shipping lines, transportation businesses, logistics companies, and other service providers, must regard technology adoption as a long-term development process (Bessid *et al*., 2020). Regarding this, Maritime transport chains could become more flexible and efficient as a result of digitalization (Raza *et al*., 2023). Moreover, Ports that digitize their operations provide a platform for other parties in the cargo, freight, and passenger environments to benefit (Becha *et al*., 2020).

In the current digital age, ports confront fierce competition in the global supply chain. The competitiveness and sustainability of the national economy are enhanced by smart ports, which are high-performing ports that use information and communications technology to provide a range of smart applications (Alzate *et al*., 2024). Furthermore, Optimizing the use of the existing infrastructure is the primary objective of digital innovation, which is an essential component of ports that aim to be competitive (Yau *et al*., 2020).

1.2 Research Background and Rationale

This research is considered a continuation of the previous study prepared by the authors (Farahat *et al*., 2025); in the latest study, the readiness of Egyptian ports to transform into smart ports was studied, focusing on critical issues such as human resource development, automation, sustainability, safety, and cybersecurity. Semi-structured interviews with port managers, experts, and stakeholders were done using a qualitative, deductive method. Thematic analysis of these interviews gave vital insights into Egypt's accomplishments and obstacles in adopting smart ports. Notably, the study concluded major advances in Egyptian port automation, particularly through the use of Terminal Operating Systems (TOS), while emphasizing human resource development as a major concern due to training gaps and resistance to change. While the first research successfully described the conceptual framework shown in Figure (1) for smart port adoption, it focused on identifying the key pillars and evaluating the current state of Egyptian ports. However, it did not conduct an empirical study on the correlations between the variables conducted from the literature and interviews.

This research aims to complete this research process by empirically examining these relationships. Specifically, it investigates how human resources development, automation in port operations, sustainability requirements, port security, and safety measures, cybersecurity systems, digitalizing port systems, and the integration of the port community influence the readiness of Egyptian ports for smart port transformation.

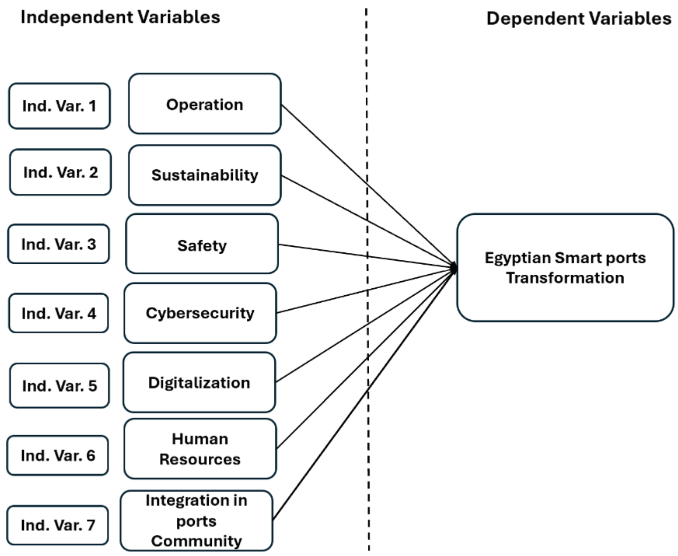

Figure 1: Conceptual Framework conducted from Initial Research

Literature Review

2.1 Conceptualizing smart ports

The idea of a "smart port," which first emerged in 2011, suggests using new technology to improve the performance and transparency of traditional port services by enhancing their dynamic and interactive capabilities (Paraskevas *et al*., 2024). Ports are beginning to consider themselves "smart" as a result of this major digital transformation. Processes are being digitalized, and communities inside the port are becoming more linked, resulting in considerable improvements in operational efficiency, regulatory compliance, and customer satisfaction (Molavi *et al*., 2020). Smart ports, being vital nodes in the world's supply chain, have the ability to

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serve as logistics information exchange hubs for their regional transportation ecosystem. The new technological foundation of smart ports, autonomous ships, digital rail, smart containers, smart contracts, and many more intelligent technologies linked via a port's digital information hub will result in tremendous value gains (Triska *et al*., 2024).

The smart port has been identified in multiple ways. These definitions all have one thing in common: they express a technology-centric mindset. Nonetheless, (Karli *et al*. 2021) defined smart ports as "sustainable ports that utilize facilities and port infrastructure in the most effective way possible by employing digital technology at the port efficiently, aiming for maximum revenue at the lowest possible cost." They have worries about worker safety and security, making use of renewable energy resources, and conducting energy and environmental management, and they have added financing elements in their definition of a smart port. The primary rationale for adding finance in the smart port dimension is that smart ports serve the same purpose as traditional ports. As a result, finances are vital. (Rajabi. *et al*. 2018) Explained that a smart port is completely automated and has all of its equipment and infrastructure connected by the IoT (Internet of Things). They said that the smart port's primary objectives are energy awareness, economic development, and effective logistical operations and that IoT is actually what propels the productivity of smart ports.

A smart port is more than just a digital technology application. Smart ports are essential for advancing and bolstering international trade since they incorporate digitalization and fourth-industrial revolution technology (Behdani, 2023). Being "smart" means making a port more competitive and appealing to consumers and users as well as the general public (Lee *et al.,* 2016). Smart port takes into account the needs of port terminal logistics operators. In addition, a smart port enhances the security, dependability, and fluidity of information exchanges and real-time decision-making by relying on the automation of the port terminal's operations and equipment as well as the interconnection of the stakeholders in the port logistics chain (Douaioui *et al*. 2018). It is advised (Sakty. 2016) that stakeholders and seaport authorities promote quality jobs and working conditions, encourage technology investment, implement a single window concept, spread out tracking and tracing technologies, improve the capacity and quality of the infrastructure, improve the environmental and waste management systems, and develop and implement sustainable energy action to overcome the challenges and obstacles facing the transformation of ports into smart logistics nodes.

2.2 Lessons learned from successful smart ports Implementations

Successful smart port implementations worldwide demonstrate that digitalization, automation, and sustainability are key to enhancing port efficiency, competitiveness, and environmental responsibility. The Port of Hamburg integrates smart logistics and energy management to optimize transport flows, reduce emissions, and improve operational efficiency through IoT-based cloud networks (Smart Port Development Policies in Asia and the Pacific, 2021). Singapore's TUAS Port is set to become fully automated by 2040, utilizing AI-driven systems like SAFER and OptEVoyage to streamline vessel arrivals and improve supply chain resilience (PSA Singapore, OptEVoyage, World Port Sustainability Program). The Port of Rotterdam leverages Industry 4.0 technologies, including IoT, AI, and digital twins, to optimize logistics, reduce waiting times, and advance toward full automation (Port of Rotterdam, 2024). These cases highlight that successful smart ports prioritize real-time data integration, sustainability, and collaborative management, reinforcing their role in the future of global maritime trade (Navigate to the Future: Maritime 2050, 2019)

The existing smart ports that are present worldwide show that smart ports are more productive, competitive, and efficient. To increase security, reduce energy, and accomplish more with less, port organizations seek smart ports to use real-time data with a collaborative management style. (Navigate to the Future: Maritime 2050, 2019). Green and digital smart ports have improved access to resources for sustainable development, industrial settings, and logistics. These automated ports prioritize maritime environmental considerations while using the latest technologies. There are several key pillars driving smart port efforts around the world, and while each has its own focus, many of them tend to overlap and reinforce one another.

The most advanced smart ports are working on energy management and environmental impact and have a strategy to deal with these issues. On the opposite, other ports are working on multifunctional initiatives (Molavi *et al*., 2020). So, this research explores the influence of different smart port variables, providing a tailored roadmap for transforming Egyptian ports into smart ports. This roadmap will allow port authorities and managers to improve key areas and increase their efficiency, preparing them for smart port transformation in accordance with global standards and sustainable development needs.

2.3 Hypothesis Development

This research investigates the transformation of Egyptian ports into smart ports by examining critical variables that influence this transformation. The study builds upon prior findings presented in the conceptual framework developed for Egyptian ports, where key pillars were identified, including human resources development, automation in port operations, sustainability requirements, port security, and safety measures, cybersecurity systems, digitalizing port systems, and integration of the port community. Based on the variables identified through the literature review and insights gained from semi-structured interviews with experts, the following hypotheses were developed in alignment with the formulated conceptual framework.

- H1: Human resources development has a significant impact on Egyptian smart port transformation.
- H2: There is a significant impact of automation in port operations on Egyptian smart port transformation.
- H3: Sustainability requirements have a significant impact on Egyptian smart port transformation.
- H4: Port security and safety measures have a significant impact on Egyptian smart port transformation.
- H5: Cybersecurity systems have a significant impact on Egyptian smart port transformation.
- H6: Digitalizing port systems has a significant impact on Egyptian smart port transformation.
- H7: The integration of the port community has a significant impact on Egyptian smart port transformation.

Research Methodology

3.1 Research Structure

This study employs a deductive approach to investigate the readiness of Egyptian ports for smart port transformation. The research is divided into phases. The first phase identifies the key pillars of smart ports through a comprehensive review of previous studies. The second phase involves a survey analysis, which is based on correlation analysis and structural equation modeling (SEM), to validate the theoretical framework and assess the readiness of Egyptian ports for smart transformation. Then, a roadmap is conducted, offering deeper insights into how elements interact to support or hinder the transformation to a smart port.

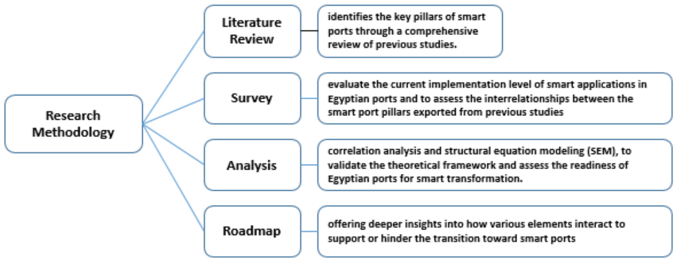

Figure 2: Research structure

Source: Own Elaboration

3.2 Data Collection and Sampling

The study's second phase utilized a structured survey to evaluate the readiness of Egyptian ports for smart transformation. The survey, designed based on hypotheses (H1-H7) derived from a comprehensive literature review, consisted of 25 Likert-scale questions organized into nine sections. These sections are as follows:

1. Socio-demographic information
2. Human resources development (H1)
3. Automation in port operations (H2)
4. Sustainability requirements (H3)
5. Port security and safety measures (H4)
6. Cybersecurity systems (H5)
7. Digitalizing port systems (H6)
8. Integration of the port community (H7)
9. Open-ended questions

The research population included 427 entities, comprising 412 Alexandria Navigation Chamber-registered enterprises and 15 Egyptian commercial ports. These stakeholders were chosen because commercial ports play an important role as trade and logistics hubs, processing the vast majority of Egypt's imports and exports. Their readiness for smart transformation has a direct impact on the country's economic performance and global competitiveness.

The study employed a cluster random sampling method, dividing the population into location-based groups, with ports and their stakeholders as clusters. A sample size calculator determined a minimum of 203 respondents for statistical validity, and data was collected from 210 employees in Egypt's ports and port stakeholders.

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3.3 Analysis

To test the hypothesis, SPSS and AMOS 18 were employed to apply correlation analysis and structural equation modeling (SEM) to examine relationships between factors and smart port transformation. The research evaluated reliability and validity and carried out frequency analysis, confirmatory factor analysis, normality testing, and multicollinearity analysis.

Correlation analysis is utilized to point out the significance of relationships among different variables influencing smart port transformation. Structural equation modeling (SEM) is then used to validate and test the study hypothesis, leading to a well-documented and systematic Knowledge of variables that affect smart port readiness. Having developed a roadmap and the major components of making Egyptian ports smart ports, SEM is an all-encompassing way of analyzing several interactions at once, giving further insight into how different components interface to enable or hinder change. Ethical concerns were given due consideration while conducting the research. Participants were informed about the purposes of the research, the voluntary nature of participation, and their freedom to withdraw at any point. The responses of participants were maintained as anonymous and confidential to protect data and participants' privacy.

Results

This section evaluates the preparedness of Egyptian ports for transitioning into smart ports by examining key elements, including the development of human resources, the level of automation, efforts toward sustainability, cybersecurity measures, digitalization processes, and the integration of the port community. The following section presents the quantitative analysis and hypothesis validation.

4.1 Survey Sample and Population:

The research population was drawn from the 412 companies registered with the Alexandria Navigation Chamber, along with 15 commercial ports in Egypt, encompassing a wide range of stakeholders. This selection results in a total population size of 427 entities.

Commercial ports and their stakeholders were selected as the research population for the reason that the majority of Egypt's imports and exports pass through commercial ports, which serve as trade and logistics hubs. Their readiness for smart transformation has a direct impact on the country's economic performance and global competitiveness.

Non-commercial ports, such as military, fishing, and recreational ports, were excluded. The reason for excluding these ports is because they play a little part in international trade and commerce. Their contribution to the national economy and trade efficiency is minimal when compared to commercial ports, making them less relevant to a study on smart port transformation. Furthermore, previous research has primarily focused on commercial ports because of their importance in trade and economic activity. This emphasis on commercial ports strengthens the rationale for excluding non-commercial ports.

A cluster random sampling method will be employed to select the study sample. According to (Acharya *et al.* 2013), this is a two-step procedure that divides the population into location-based groups, such as villages, schools, facilities, and blocks. In this study, the clusters are defined as ports and their stakeholders. The study sample is calculated using the sample size calculator, which calculates the minimum number of necessary samples to meet the desired statistical constraints. These resulted in a sample size of 203, which means 203 or more Surveys are needed to have a confidence level of 95% that the real value is within ±5% of the surveyed value.

4.2 Respondent Profile

The descriptive statistical analysis examines the characteristics of 210 Egyptian employees based on work position, years of experience, and education level using percentage analysis. The results indicate that 43.3% hold managerial positions, 24.3% are in administrative roles, 11.4% specialize in technical roles, and 21% occupy other roles. Regarding experience, 69% have over 10 years of experience, while 11.4% have 7-10 years. In terms of education, 39% hold a bachelor's degree, 43.8% have a master's degree, and 17.1% possess a doctorate.

Table 1: Respondents' profile

1.	Frequency	Percent	Total
Work Position			
Manager	91	43.3	210
Technical	24	11.4	
Administrative Staff	51	24.3	
Other	44	21.0	
Work Years			
Less than one year	6	2.9	210
1-3	16	7.6	
4-6	19	9.0	
7-10	24	11.4	
More than 10	145	69.0	

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1.	Frequency	Percent	Total
Level of Education			
Bachelor	82	39.0	210
Master	92	43.8	
Doctorate	36	17.1	

4.3 Descriptive Analysis

Descriptive analysis is essential to gain an understanding of the data to be analysed. In this research, descriptive statistics are employed for each variable in the study. These statistics include standard deviation, minimum, maximum, and mean, as shown in Table 2.

Table 2: Descriptive analysis of research variables

	N	Minimum	Maximum	Mean	Std. Deviation
Human Resources Development	210	1.00	5.00	2.6190	1.01549
Automation in Port Operations	210	1.00	4.00	1.7238	.75768
Sustainability Requirements	210	1.00	5.00	2.4000	.86506
Port Security and Safety Measures	210	1.00	3.00	1.7619	.64182
Cybersecurity Systems	210	1.00	5.00	1.8190	.71593
Digitalizing Port Systems	210	1.00	5.00	1.8476	.74860
Integration of the Port Community	210	1.00	4.00	1.7524	.66030
Egyptian Smart Port Transformation	210	1.00	5.00	1.8429	.76344

Source: Own Elaboration

To prepare the data for analysis, responses to the 25 Likert-scale statements were grouped to create composite scores for each of the seven key pillars: Human Resources Development (HRD), Automation in Port Operations (APO), Sustainability Requirements (SR), Port Security and Safety Measures (PSSM), Cybersecurity Systems (CS), Digitalizing Port Systems (DPS), and Integration of the Port Community (IPC). Each pillar was assessed through 2 to 4 related statements. For each participant, the average of the relevant statements was calculated to generate a single score representing that specific construct. These composite scores formed the basis for the descriptive statistics, correlation analysis, reliability and validity testing, and structural equation modeling used in the study. It is important to note that some statements were excluded from the final analysis due to low factor loading during validity testing. The complete survey, along with the alignment of each statement to its corresponding construct, is provided in Appendix A.

4.4 Validity and Reliability Testing

The section verifies that the study's variables possess validity and reliability to guarantee accurate measurement and interpretation. The researchers assessed validity by employing Average Variance Extracted (AVE) and Factor Loadings (FL) to evaluate the effectiveness of their measures in representing the intended concepts. AVE scores were all above 0.5 and FL values above 0.40, acceptable thresholds (Hair *et al.*, 2016; Yong and Pearce, 2013). Reliability, reflecting the consistency and reliability of the findings, was tested via the KMO test and Cronbach's alpha. According to the literature, Cronbach's alpha values of between 0.7 and 0.9 are strong consistency, while values below 0.6 suggest weak reliability (Sürücü and Maslakci, 2020). Among all variables, Human Resources Development (HRD) proved to be the most reliable.

$$\alpha = .933,\ AVE = 83.226\%,\ KMO = .853$$

The factors of Automation in Port Operations (APO), Sustainability Requirements (SR), Port Security and Safety Measures (PSSM), Cybersecurity Systems (CS), Digitalizing Port Systems (DPS), and Integration of the Port Community (IPC) display moderate to high levels of reliability (Cronbach's α from .700 to .825) along with validity. The Egyptian Smart Port Transformation (ESPT) demonstrates strong internal consistency.

$$\alpha = .849,\ AVE = 76.920\%,\ KMO = .704.$$

Overall, the results show that the data is both reliable and valid, making it suitable for further analysis (Rozali *et al.*, 2022).

Table 3: Validity and reliability test

Variables	KMO	AVE %	Cronbach's α	Statements	Factor Loading
Human Resources Development	.853	83.226	.933	HRD1	.773
				HRD2	.865
				HRD3	.877
				HRD4	.815
Automation in Port Operations	.500	77.278	.703	APO1	.773
				APO2	.773
Sustainability Requirements	.500	85.138	.825	SR2	.851
				SR3	.851
Port Security and Safety Measures	.500	84.920	.821	PSSM1	.849
				PSSM3	.849
Cyber security Systems	.500	76.766	.700	CS1	.768
				CS3	.768

Variables	KMO	AVE %	Cronbach's α	Statements	Factor Loading
Digitalizing Port Systems	.500	83.108	.793	DPS1	.831
				DPS2	.831
Integration of the Port Community	.500	75.302	.700	IPC1	.753
				IPC2	.753
Egyptian Smart Port Transformation	.704	76.920	.849	ESPT1	.773
				ESPT2	.831
				ESPT3	.703

Source: Own Elaboration

*HRD = Human Resources Development, APO = Automation in Port Operations, SR = Sustainability Requirements, PSSM = Port Security and Safety Measures, CS = Cybersecurity Systems, DPS = Digitalizing Port Systems, IPC = Integration of the Port Community, ESPT = Egyptian Smart Port Transformation. The number following each acronym (e.g., "1" in HRD1) indicates the order of the statement within that construct.

4.5 Testing Research Hypotheses

Both correlation analysis and structural equation modeling (SEM) are used to assess the research hypotheses. Correlation analysis was employed to estimate the strength and direction of relationships between variables, using a correlation coefficient ranging from -1 to +1. Since the data wasn't the typical bell-curve shape, a different type of correlation called Spearman's rank correlation (Spearman's r) is used. This method works well when data isn't normally distributed. Table 3 shows the correlation coefficients among the research variables, revealing the following key findings:

- Human resources development (HRD) and Egyptian smart port transformation (ESPT) have a moderate positive correlation ($r = 0.354$, $p < 0.05$).
- ESPT has a moderate positive correlation with automation in port operations (APO) ($r = 0.411$, $p < 0.05$).
- A weak to moderate positive correlation exists between ESPT and sustainability requirements (SR) ($r = 0.222$, $p < 0.05$).
- ESPT shows a weak but significant positive correlation with port security and safety measures (PSSM) ($r = 0.171$, $p < 0.05$).
- A moderate positive correlation is found between ESPT and cybersecurity systems (CS) ($r = 0.281$, $p < 0.05$).
- ESPT also has a moderate positive correlation with digitalizing port systems (DPS) ($r = 0.287$, $p < 0.05$).
- A moderate positive correlation is observed between ESPT and integration of the port community (IPC) ($r = 0.338$, $p < 0.05$).

These correlations suggest that Egypt's transition to smart ports is influenced by various factors, including human resources development, automation in port operations, sustainability requirements, cybersecurity systems, digitalization of port systems, and the integration of the port community.

Table 4: Research variable correlation matrix

		1	2	3	4	5	6	7	8
HRD	R	1.000							
	Sig.	.							
	N	210							
APO	R	.301**	1.000						
	Sig.	.000	.						
	N	210	210						
SR	R	.506**	.311**	1.000					
	Sig.	.000	.000	.					
	N	210	210	210					
PSSM	R	.201**	.313**	.431**	1.000				
	Sig.	.003	.000	.000	.				
	N	210	210	210	210				
CS	R	.065	.341**	.093	.400**	1.000			
	Sig.	.346	.000	.180	.000	.			
	N	210	210	210	210	210			

DPS	R	.250**	.393**	.374**	.456**	.329**	1.000		
	Sig.	.000	.000	.000	.000	.000	.		
	N	210	210	210	210	210	210		
IPC	R	.277**	.315**	.332**	.321**	.331**	.387**	1.000	
	Sig.	.000	.000	.000	.000	.000	.000	.	
	N	210	210	210	210	210	210	210	
ESPT	R	.354**	.411**	.222**	.171*	.281**	.287**	.338**	1.000
	Sig.	.000	.000	.001	.013	.000	.000	.000	.

Source: Own Elaboration

4.6 Structure Equation Modelling

The study used Structural Equation Modeling (SEM) to examine the impact of various factors on Egyptian smart port transformation. The findings shown in Table 5 are summarized as follows:

- **Human Resources Development (H1)**: A significant positive impact on Egyptian smart port transformation was found (p = 0.000, estimate = 0.209). HRD explains 14.8% of the variance, supporting the hypothesis.
- **Automation in Port Operations (H2)**: A significant positive effect on smart port transformation was observed (p = 0.043, estimate = 0.395). Automation explains 15.7% of the variance, supporting the hypothesis.
- **Sustainability Requirements (H3)**: No significant effect on smart port transformation ($p > 0.05$). Sustainability requirements explain only 6.5% of the variance, so the hypothesis is not supported.
- **Port Security and Safety Measures (H4)**: A non-significant negative effect was found ($p > 0.05$). These measures explain 2.8% of the variance, so the hypothesis is not supported.
- **Cybersecurity Systems (H5)**: No significant effect on smart port transformation ($p > 0.05$). Cybersecurity systems explain 6.0% of the variance, so the hypothesis is not supported.
- **Digitalizing Port Systems (H6)**: A non-significant negative effect was found ($p > 0.05$). Digitalizing port systems explains 4.4% of the variance, so the hypothesis is not supported.
- **Integration of the Port Community (H7)**: A significant positive effect on smart port transformation was found (p = 0.018, estimate = 0.538). It explains 10.9% of the variance, supporting the hypothesis.

In conclusion, human resources development, automation in port operations, and integration of the port community have significant positive impacts on Egyptian smart port transformation, while sustainability requirements, port security, and safety measures, cybersecurity systems, and digitalizing port systems do not.

Table 5: Structure equation modelling results

			Estimate	S.E.	C.R.	P	Hypoth-esis	R^2
ESPT	<---	HRD	.209	.068	3.062	.002	H_1	.148
ESPT	<---	APO	.395	.195	2.025	.043	H_2	.157
ESPT	<---	SR	.048	.118	.408	.683	H_3	.065
ESPT	<---	PSSM	-.282	.182	-1.543	.123	H_4	.028
ESPT	<---	CS	.050	.206	.242	.809	H_5	.060
ESPT	<---	DPS	-.115	.123	-.936	.349	H_6	.044
ESPT	<---	IPC	.538	.227	2.367	.018	H_7	.109

Discussion

When examining Egyptian ports' preparations for the transition to smart ports, the research correlation analysis revealed several strong correlations; however, certain elements had inconsequential relationships.

***Development of Human resources*:** It is easy to recognize the connections between smart port preparedness, staff training, and the continuous pursuit of new and creative methods to enhance port operations. New opportunities frequently call for new methods of completing tasks that involve human labor. This result supports the findings of Robert (2020) and Paraskevas (2024), who noted a connection between the employment of smart technology in port operations and personnel training and development. Ports with robust HRD programs are better able to handle the complexity of smart port technologies, according to a number of studies.

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Port automation: port automated systems increase productivity, enhance the efficiency of workflow, and minimize mistakes. Berlin and Eriksson (2021) noted that applying automation technologies in port operations, especially in handling cargo, management of inventory, and logistics integration, is associated with enhanced operational flexibility and efficiency. These attributes are considered crucial indicators of successful smart port transformations. This viewpoint is also strengthened by Karas (2020a), who concludes that automation can lead to considerable time and operational cost savings, factors that are central to enhancing the competitiveness of a port in the global market.

Integration of Port Community: Othman *et al*. (2022) and Gizelis *et al*. (2022) emphasize that the progression of smart port development is significantly dependent on robust collaboration and efficient communication channels among shipping lines, port authorities, and diverse stakeholders. The positive link between port community integration and readiness for smart port transformation highlights how crucial stakeholder engagement is to make the transition a success. According to their results, prompt information exchange and well-coordinated decision-making are essential cornerstones of a well-functioning, integrated smart port system.

Sustainability Requirements: Notwithstanding the widespread international focus on sustainable development, the outcomes of this investigation did not establish a statistically significant association between a port's readiness for smart technologies and adherence to sustainability criteria. This observation diverges from the findings reported by Garg *et al*. (2023), who posited sustainability as a salient factor propelling the evolution of smart ports. In the Egyptian context, however, this connection appears weaker, possibly due to the current prioritization of technological advancements over environmental concerns. Min's (2022) work confirms that although sustainability is essential, it becomes secondary to smart port initiatives where operational efficiency and cost-effectiveness dominate.

.***Port Security and Safety Measures:*** Another important insight is that port safety and security measures do not show a significant connection with smart port readiness. Simola *et al*. (2023) explain that although security and safety are significant aspects of port operations, they do not necessarily contribute to smart port readiness unless they are designed to respond to the requirements of smart technologies specifically. Reva (2020) backs this up, suggesting that existing security standards are frequently insufficient to manage the complex and growing difficulties connected with smart port systems.

Cybersecurity Systems: Douaioui *et al*. (2018) highlighted the critical dependence of smart port efficiency on strong and secure network management systems. However, the absence of a material relationship between smart port preparedness and cybersecurity infrastructure in this study shows that this industry is underdeveloped and requires further combined effort and dedicated investment. Reva (2020) points out that many ports still haven't put in place full cybersecurity strategies that match their digital transformation goals. Progress in this crucial area of development may be hampered in the Egyptian context by the scant empirical data relating cybersecurity to smart port readiness.

Digitalising Port Systems: Moreover, Egyptian ports are still in the early stages of digitalization, as reflected in the weak correlation observed between smart port readiness and the digitalization of port infrastructure. While digitalization is a fundamental component of smart port development, Dalaklis *et al*. (2022) note that its impact may not be immediately apparent. This is particularly true in contexts where foundational infrastructure and technological adoption are still emerging, as Karas (2020) also points out.

Roadmap to Smart Port Transformation

This research offers a model for the evolution of Egyptian ports towards smart port status. The proposed framework, informed by both empirical investigation and a review of literature, centers on the strategic incorporation of technology, the effective alignment of stakeholder interests, and the enhancement of operational processes. While Existing smart port initiatives need more coordination and integration to achieve long-term sustainability. The plan employs a staged approach that starts with gap analysis before moving on to prioritizing automation, cybersecurity, and sustainability. Pilot programs are then implemented to pilot and harden technologies, develop workforce capability, and ensure seamless system integration. Regular evaluation and optimization cycles provide long-term scalability by monitoring progress and optimizing systems for technology refreshes. This stepwise approach aims to transform Egyptian ports while fostering a secure and sustainable working environment.

1. Assessment Phase
    - Conduct comprehensive audits of existing infrastructure and digital readiness.
    - Identify key gaps in automation, cybersecurity, and sustainability.

- Benchmark against leading global smart ports.

2. Prioritization Phase
   - Focus on integrating digital solutions with current port operations.
   - Develop training programs for port employees on smart port technologies.
   - Encourage policy reforms to facilitate digitalization efforts.
3. Pilot Testing and Scaling
   - Conduct small-scale pilot projects to evaluate automation solutions and digital platforms.
   - Assess cybersecurity measures to ensure resilience against cyber threats.
   - Expand successful projects to multiple port terminals.
4. Implementation Phase
   - Implement comprehensive digital infrastructure, including IoT technologies and AI-driven analytics.
   - Enhance cybersecurity processes to safeguard sensitive data.
   - Collaborate with international smart port leaders to transmit technology.
5. Continuous Monitoring and Optimization
   - Apply key performance indicators (KPIs) to measure smart port efficiency.
   - Create real-time data dashboards for operational monitoring.
   - Ensure ongoing training and policy adaptations to keep pace with technological advancements.

Table (6) outlines the key principles guiding the transformation of Egyptian ports into smart ports, along with the main challenges standing in the way—such as internal resistance to change, limitations in available technology, and environmental constraints. It also suggests realistic, actionable steps to overcome these obstacles and clearly identifies the various organizations involved, from local port authorities to national ministries, ensuring each has defined responsibilities. The goal is to develop a port infrastructure that is technologically advanced, well-coordinated, and highly efficient. These findings are grounded in both survey responses and expert perspectives, offering a reliable basis for assessing where Egyptian ports currently stand and what steps are needed moving forward. If the proposed plan is carried out effectively, it can significantly boost operational performance, help ports meet global standards, and enhance Egypt's position in the international maritime sector.

Table 6: Summary of key transformation concepts, barriers, solutions, and entities in charge

Transformation Concept	Barriers	Solutions	Institution in Charge
Digital Infrastructure & Automation	Limited automation in cargo tracking and terminal operations, reliance on manual labor	Implement a full Terminal Operating System (TOS) and Port Community System (PCS) for real-time tracking and integration.	Ministry of Transport, Port Authorities
Human Resources Development	Resistance to technology, lack of skills in digital tools	Develop training programs for employees on digital tools and incentivize technology adoption.	Port Authorities, Port Training Institute (PTI), Egyptian Ministry of Manpower
Stakeholders' integration	Poor integration among port community members	Implement a unified digital system for stakeholders, such as a single-window platform.	Ministry of Transport, Port Community System
Cybersecurity Systems	Inadequate cybersecurity infrastructure to protect port systems	Establish a multi-layered cybersecurity protocol with regular security audits and employee training	Ministry of Communications, Port IT Department
Digitalization of Port Systems	Reliance on paper-based processes, low digital integration	Transition to digital documentation and develop an integrated Port Community System	Ministry of Transport, Port IT Department
Financial Investment & Infrastructure	Budget constraints, limited investment in advanced infrastructure	Establish public-private partnerships (PPPs) and seek international funding for smart port infrastructure	Ministry of Investment, Port Authorities

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Customer and User Experience	Long waiting times, limited digital communication with port users	Develop a user-friendly interface for port customers with real-time tracking and support	Port Authorities, Port IT Department
Resilience and Adaptability	Limited agility in responding to market and operational disruptions	Implement flexible infrastructure and agile decision-making processes for rapid adaptation to changes	Port Management, Port Authorities
Environmental Monitoring	Poor monitoring of emissions and pollutants	Implement environmental monitoring systems for tracking emissions, noise, and water quality.	Ministry of Environment, Port Management
Energy Management	High energy consumption and reliance on non-renewable sources	Shift to renewable energy sources (solar, wind) and implement energy-saving measures	Ministry of Electricity, Port Authorities

Conclusion and Implications

7.1 Conclusion

To increase operational effectiveness, sustainability, and global competitiveness, traditional Egyptian seaports must be converted into smart ports. The findings of this study identified several key dimensions exerting a considerable influence on a port's preparedness for smart transformation. These critical aspects encompass human resource development, the automation of port operations, and the integration of the port within the broader community. These are some of the main areas in facilitating the smart port ecosystem transformation. However, areas such as elevated sustainability standards, enhanced port security, stronger safety cultures, advanced cyber defense solutions, and digital enablement have not shown a significant correlation with Egyptian port preparedness for smart transformation. This emphasizes how urgently more organized, awareness-driven planning is required in order to adequately handle these crucial areas. Egyptian ports can start implementing smart technology gradually, increase operational effectiveness, and become closer to global best practices by taking a methodical, gradual approach. This would ultimately help the growth of a stable and competitive maritime industry.

7.2 Implications

This study offers a noteworthy theoretical advancement to the developing body of knowledge concerning smart port transformation. Specifically, it emphasizes the significant roles of human resource development, automation implementation, and the inclusion of the port community within the smart port paradigm. These topics are in line with global debates that highlight how digital transformation can improve port operations. At the same time, the results indicate a need for more theoretical research into the relationship between smart port readiness and sustainability, cybersecurity, and safety measures—at least in the context of Egyptian ports.

From a practical perspective, the study offers useful guidance for stakeholders, port authorities, and policymakers committed to advancing smart port strategies. Promoting automation and investing in the development of human capital should be prioritized to support digital adoption. In parallel, achieving effective integration with the broader port community requires coordinated action among all involved parties. While sustainability and security were not found to be strong influencing factors in this study, they remain essential for aligning Egypt's port sector with international benchmarks. With a clear and phased implementation plan, Egyptian ports stand to improve their efficiency, strengthen long-term resilience, and elevate their position in the global maritime landscape.

7.3 Research Limitations and Further Studies

Despite the contributions of this research, several limitations should be acknowledged. One of the main constraints is the relatively small sample size, as the study was based on feedback from a limited group of stakeholders within Egyptian ports. Expanding the sample to include a broader range of ports and industry perspectives would likely yield more comprehensive insights. Additionally, the research relies primarily on stakeholder opinions rather than an in-depth technical evaluation of port infrastructure, which may limit the precision of the smart port readiness assessment.

Another limitation is the study's exclusive focus on Egyptian ports, which may reduce the generalizability of the findings to other regions with different economic, regulatory, and technological environments. Moreover, smart port transformation is a rapidly evolving process driven by continuous technological advancements. As such, a longitudinal approach would be necessary to capture its dynamic nature and changing impacts over time.

Given these limitations, future research should consider conducting comparative studies between Egyptian ports and international counterparts to identify best practices and remain aligned with global developments. Further investigation is also needed into the influence of national policy frameworks and international regulations on the pace and success of smart port initiatives. In addition, studies exploring the integration of green technologies, renewable energy solutions, and cybersecurity strategies will be essential to shaping resilient and future-ready port systems. Addressing these areas would deepen our understanding of smart port transformation and support more informed decision-making in the maritime sector.

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Appendix A

Survey

An Empirical Study for Transforming Egyptian Seaports into Smart Ports Through Suggesting a Strategic Roadmap

This appendix presents the structured survey questionnaire used to assess the readiness of Egyptian ports for smart transformation. The 25 Likert-scale items are grouped under seven investigative pillars corresponding to the study's hypotheses (H1–H7). All items were rated on a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree).

Section 1: Demographics and Background Information

- What is your current role at the port/Company?

Manager
Technician
Administrative Staff
Other (please specify)

-How many years have you worked in the port industry?

Less than 1 year
1-3 years
4-6 years
7-10 years
More than 10 years

-Level of Education

PhD
MSc
BSc

Section 1: Dependent Variable - Egyptian Smart Port Transformation (ESPT)

1- The adoption of smart port technologies will positively impact the economic performance of Egyptian ports (ESPT 1)

2- The implementation of smart technologies will significantly improve the efficiency of port operations in Egypt. (ESPT 2)

Section 2: Human Resources Development (H1)

1. The overall quality of training programs provided by ports is excellent. (HRD 1)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

2. Ports staff are frequently provided with opportunities for professional development (e.g., workshops, seminars, courses).

Strongly Agree (HRD 2)
Agree
Neutral
Disagree
Strongly Disagree

3. The port invests adequately in employee skill development. (HRD3)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

4. The training programs are highly relevant to the technological advancements in the port industry (e.g., automation, digitalization). (HRD 4)
Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

5. Human resources development is crucial for the successful transformation into a smart port. (HRD 5)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

Section 3: Automation in Port Operations (H2)

6. Implementing automation in port operations will significantly enhance the efficiency of port activities. (APO 1)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

7. Automation technologies (e.g., automated cranes and self-driving vehicles) are essential for smart port transformation. (APO 2)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

8. The Egyptian port has already seen improvements in operations due to automation technologies. (APO 3)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

Section 4: Sustainability Requirements (H3)

9. Enforcing sustainability requirements will facilitate the transformation of Egyptian ports into smart ports. (SR 1)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

10. The Egyptian port has implemented effective sustainability practices (e.g., waste management and energy efficiency). (SR 2)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

11. Sustainability initiatives are prioritized in Egyptian port's strategic plans. (SR 3)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

Section 5: Port Security and Safety Measures (H4)

12. Improving port security measures will positively affect the smart port transformation. (PSSM 1)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

13. Egyptian ports have made significant improvements in safety measures in recent years. (PSSM 2)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

14. Enhanced security measures are essential for the successful implementation of smart port technologies. (PSSM 3)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

Section 6: Cybersecurity Systems (H5)

15. Implementing robust cybersecurity systems is crucial for the smart port transformation. (CS 1)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

16. Egyptian ports have effective cybersecurity measures in place to protect against digital threats. (CS 2)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

17. The risk of cyber threats is a major concern in the digitalization of port operations. (CS 3)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

Section 7: Digitalizing Port Systems (H6)

18. Digitalizing port systems will enhance the efficiency and effectiveness of port operations. (DPS 1)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

19. Digital systems are well-integrated into our daily port operations. (DPS 2)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

Section 8: Integration of the Port Community (H7)

20. There is a significant positive relationship between the integration of the port community and the transformation of Egyptian smart ports. (IPC 1)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

21. Collaboration with stakeholders (e.g., shipping companies and logistics providers) is crucial for the smart port transformation. (IPC 2)

Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

Section 9: Open-Ended Questions

22. Please describe any specific initiatives or projects that have significantly contributed to the smart port transformation in your experience.

23. What additional measures or resources do you believe would help further the smart port transformation at Egyptian ports?