EMERGING ECONOMY SMART PORT ADOPTION: CHALLENGES AND OPPORTUNITIES IN DIGITAL MARITIME INFRASTRUCTURE TRANSFORMATION

Mohamed Elhussieny

College of Maritime Transport and Technology, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

hosinymohamed@aast.edu

Keywords: Smart port technology, Digital transformation, Alexandria Port, Regional development, Environmental management, Digitalization, sustainability.

1. **ABSTRACT:** Technological progress in the global maritime sector is both an opportunity and challenge for developing nations adopting smart port technologies. While ports such as Rotterdam, Singapore, and Hamburg have success stories in the digitalization of global shipping, developing nation ports often lack basic infrastructure and other institutional gaps. Between 2020 and 2025, we focused on smart port technology in six emerging economy port case studies: Lagos, Alexandria, Conakry, Tema, Casablanca and Santos. We identified the persistent issues using the digital transformation metrics framework based on advanced ports. Stakeholders in the fragmented systems demonstrated inadequate operational processes, old and irrelevant policies, and low levels of technical know-how. Problems such as the operational systems, electricity, and internet were interrelated and compounded each other. Alexandria port is exemplary. It shows that operational sophistication is possible for emerging economy ports through global partnerships with international terminal operators, regional development, bank financing, and innovative cross-border collaboration. Alexandria Port is operationally self-sustaining and does not need to adopt the Northern European systems.

   With regards to this, the most illustrative is Misr terminal: combining clean energy systems with LED lights and smart digital systems for environmental management. The more general finding across all six cases identifies 'functioning' pragmatic solutions: the gradual implementation of technology instead of jumping to full automation, the prioritization of sequenced improvements based on the immediacy of value, and the integrated cross of digitalization and sustainability, as opposed to the compartmentalization of these two objectives.

2. INTRODUCTION

Digital transformation together with its rapidly-evolving concept of 'Smart8Ports,' according to the literature, is currently the reshaping the landscape of maritime logistics. Such changes aimed at improving productivity, safety, and, to a lesser degree, sustainability will not be welcomed. Instead, they will be offered for standards compliance to remain competitive in the global supply chain (Almeida, 2023). There is an overwhelming number of success stories that openings of new global centers, with ports of Rotterdam, Singapore and Hamburg standing out. Far less attention has been given to how ports in emerging economies are being developed. It is in the developing world where the socio-economic aspects are more pronounced and the ambition of transforming the economy with new digital technologies is facing scary infrastructural and institutional obstacles(Sarkar et al., 2022).

This paper, as such, intends to fill this critical void in maritime scientific research with a comparative multi-case study analysis of smart port adoption pertaining to six emerging economy strategically significant ports: Lagos (Nigeria), Alexandria (Egypt), Tema (Ghana), Conakry (Guinea), Casablanca (Morocco), and Santos (Brazil) (Spyridakis, 2022). Much of the emphasis of this study is aimed at

pervasive policy gap in which the black hole of dark, complex, and liquid uncharted boundary conditions is found, rather than a simple review of the myriads of challenges to be met. In particular, we will:

- Identify and categorize the various unique technological and non-technological challenges these ports encountered in their attempts to attain the smart port status between the years 2020 to 2025.
- To determine context gaps, define sets of metrics based on proven global best practices, and measure digital transformation change to best practice metrics.
- Using more successful case studies and Alexandria Port as a primary benchmark for scalable, financially sustainable models, define and assess critical success factors and adaptive strategies.
- Focus on primary policy recommendations to inform national strategies on port development as well as guide sectoral development assistance for developing countries.

The following sections will analyze the literature on smart ports, with a special emphasis on the developing countries context. Next, we explain the methodology, which is based on the analysis of comparative case studies. After that, presenting the core of the paper, which will consist on the cross-case analysis, followed by a case study of Alexandria Port and its discussed wider applicability(Elhussieny et al., 2023). In the end giving a synopsis of the most relevant findings and the corresponding set of policy recommendations.

In these contexts, the digital transformation process is markedly different and often requires the concurrent investment in the physical and institutional underpinning infrastructure needed to use advanced smart systems. This type of simultaneous development, akin to leapfrogging, adds layers of complexity and risk, and is in need of scholarly analysis, which this study attempts to provide.

3. LITERATURE REVIEW

The smart port more than just automation, as discussed in the scientific literature, is the integration of the Internet, Big Data, Artificial Intelligence, 5G, and other physical infrastructures to enhance the optimization of smart port operations, security, and environmental protection (Karaś, 2020). There is, however, a noticeable gap in the literature which seems to focus of the examination of older, developed country ports and ports in developed countries where the basic physical infrastructure is mostly assumed.

3.1.The Smart Port Paradigm: A Developed World View

The smart port vision was initially conceptualized under the Port 4.0 or 'Industry 4.0' paradigm. These approaches to smart port focus more on the 'information flows' and the 'construction of the Port Community System' (PCS). These studies do not fail to emphasize predictive maintenance, automated terminal operations, borderless cyberspace results, and open other such context where: (a) there is ubiquity of high-speed and reliable connectivity; (b) there is a strong regulatory and legal framework; and (c) there is ease of availability of high capital expenditure. These models do serve a purpose of exhibiting a theoretical final point; however, the actual application is, probably, the most lacking utility when it comes to emerging economies. The more significant and advanced issues of interoperability and data governance, often mentioned as first world problems, fall into a more basic and primitive categorization within developing situations (Barrie et al., 2024).

3.2. Contextualizing Challenges in Emerging Economies

There is still a small number of studies focusing on the challenges that developing countries' ports experience. These studies point to a different hierarchy of barriers. The most important is the structural deficit, especially the unreliability of electricity and the inadequacy of quality broadband. The financial viability of smart port initiatives within developing economies remains another unique challenge. Most government support is limited due to issues of national

scale balance; hence, external funding or Public-Private Partnerships (PPPs) must be relied upon. Research indicates that the performance of PPPs within this area is extremely the outcome of the concession arrangement, the level of prevailing geopolitics, and the risk assessment of the situation by foreign investors(Sadiq et al., 2021).

3.3. The Need for a Comparative, Context-Specific Approach

What remains largely absent in emergence regions (i.e. North Africa, and Latin America) is systematic comparative analysis that goes beyond case study approaches. The analysis of the ports of Lagos, Tema, Conakry, Casablanca, Santos and Alexandria is an attempt to fill this gap and offer a more geographically and neater holistic model to represent the challenges to the adoption of smart ports. The rest of the paper will describe the methods used in multi case studies or cross-case analysis. Thus, the aim is to enrich the theoretical conceptualization of the notion of smart in relation to emerging which, of course, requires a shift in the emerging definition to make it relevant in that context(Spyridakis, 2022).

3.4. Strategic Planning Frameworks: The Cognitive Mapping Imperative

Adoption in emerging economies smart port literature has an important yet underdeveloped dimension, which has to do with the initial cognitive mapping of the strategic terrain. An understanding of the operational ecosystem of the port, its interrelations, and its weaknesses has to be fully conceived and owned well and truly before any technology can be purchased by the port authority. This process, which terms the 'mind map' imperative, is, in essence, the construction of a complex, multi-faceted strategic framework which serves to depict the inter-relationship between infrastructure, institutions, and technology pathways. Unlike linear phased project plans which are typically 'exported' to the emerging context, the strategic planning in emerging markets has to contend with systemic instability(Wu, Zhang, & Feng, 2020).

Recent discussions have suggested that successful digital transformation may depend less on the technology itself, but rather the clarity and depth of the strategic vision underlying the initiative. As a cognitive map for all stakeholders, the vision should demonstrate how the various 'pieces' like the customs data platform and the physical security system come together to form a cohesive, functioning resilient system. In the absence of this shared model, or mind map, the deployment of the components of a smart port tends to culminate in self-contained, non-interoperable digital silos, which increase the system's complexity, but do not enhance systemic efficiency(Andrei et al., 2024). Therefore, the literature has to increase its focus on strategic pre-implementation tools that enable port leadership to address the operational environment's inherent uncertainties by transforming a chaotic bundle of challenges into a structured, albeit intricate, strategic diagram. This is an intellectual step that is necessary before investing physically or digitally in any system.

4. METHODOLOGY

To achieve the research purposes of characterizing the distinct challenges and opportunities associated with smart port adoption in developing economies and determining the key success factors, a qualitative, multi-case study comparative research design approach was used. This theory is most suitable as it enables a comprehensive contextual analysis of multifaceted and complex details in situ, where the distinctions between context and the phenomenon are poorly delineated.

4.1. Case Selection and Data Collection

The determination of the six ports of case study focusses Lagos and Santos, Conakry and Tema, Alexandria and Casablanca were deliberate to achieve a balance of geo-spatial distribution, differing levels of completed port capacity, and operational differentiation landlord and operating as well as a variety of case study port management models and strategies. The focus

of the review was the 2020-2025 period, examining the latest phase of effort undertaken for the transformation of the ports to the digital ecosystem(Sadek & Elgohary, 2020).

The collection of information was a combination of secondary sources, which was a practical requirement based on the multiple of disparate dominant sources. As examples the following can be provided.

- Port authority secondary source documents and annual returns: Based on the published strategies, investment programs, and other performance indicators pertaining to the measure and outcome of the port management with a focus on digital and sustainability development as a port and port service provider.
- Scholarly and practice-based articles of port management: Drawing from the literature review and reports from the World Bank, UNCTAD and other maritime consultative entities.

4.2. Analytical Framework: Digital Transformation Metrics

In order to surpass extract observation and assess each port systematically, a foundational analytical framework has been developed. This framework is based on existing indices of global smart ports, but for the purpose of this analysis has been distilled to the most salient metrics within the context of an emerging economy, structured around three overarching dimensions:

(Table 1): A Three-Dimensional Analytical Framework for Evaluating Smart Port Readiness in Emerging Economies

Dimension	Key Metrics (Indicators)	Rationale for Emerging Economies
I. Foundational Infrastructure	Reliability of Shore Power Supply (Uptime), Broadband Connectivity (Speed/Coverage), Physical Security Systems (CCTV/Access Control).	These are the *pre-competitive* necessities; without them, advanced smart systems fail.
II. Operational Digitalization	Extent of Port Community System (PCS) Adoption, Terminal Automation Level (TAL), Real-Time Data Sharing (Customs/Logistics).	Measures the actual integration of digital tools into core port processes.
III. Institutional & Financial Capacity	Clarity of Digital Strategy (Published Policy), Availability of Skilled IT Personnel, Reliance on PPPs for CapEx, Regulatory Agility.	Assesses the 'soft' factors that govern the sustainability and scalability of technology adoption.

This table provides the analytical starting point for evaluating the digital readiness and transformation capacity of ports in emerging economies. Unlike the smart port indices that have been devised for the Global North, this one acknowledges that ports in emerging economies function within a set of unique constraints and, therefore, must be assessed using different defining parameters that are relevant to their operational context(Sarkar et al., 2022).

4.3. Data Sourcing for Framework Metrics

Metrics were derived from Port authority reports, World Bank databases, UNCTAD assessments and Port energy regulation reports and maritime consultancy reports. The reports described the shore power reliability based on electric utility infrastructures, broadband utility assess, and the reports described the regulatory reports for telecommunications and vendor case studies. The Digital and IT strategy details describe the roadmaps and the policies, and the

reports for the pamphlets describe the road maps, the policies, and the reports for the pamphlets IT reports for the World Bank, the pamphlets described the systems, and the reports for the roadmaps, the policies, and the reports. The Digital and IT strategy details describe the roadmaps and the policies, IT and the reports for the World Bank.

Framework Overview:

The framework comprises three interrelated dimensions, with each one focusing on a critical failure element for the successful adoption of smart port technologies:

I. Foundational Infrastructure Dimension

In developing economy contexts, this underlying layer is characterized by erratic electrical grids, low coverage broadband, and weak protection systems that make advanced system technology either non-usable or very costly. The adoption literature concerning smart ports in the developing world practically all points to these infrastructural gaps as the principal limitation, rather than the secondary one that is common in analyses of developed ports(Yau et al., 2020).

II. Operational Digitalization Dimension

This dimension assesses the real and measurable infusion of digital tech to the main operational workflows of the port. The main Port Community System (PCS) adoption metrics are the level of port community system (PCS) integration (the level to which all port stakeholders- customs, shipping lines, freight forwarders, trucking companies are assimilated into a single digital system), and the real-time data sharing systems (especially those linking customs and logistics providers) Authentication Level (TAL) which measures the level of automation in cargo operations.

The reasoning on this dimension seems to be based on the fact that infrastructure is not enough on its own. For instance, a port could have all the power and fast internet it needs, yet process flows could still be siloed and manually intensive. Here, the question is whether the infrastructure which is in place is being utilized to deliver real gains in productivity. This is typically where the emerging economies struggle the most: the gap between infrastructure and productivity(Zhang et al., 2024).

III. Institutional and Financial Capacity Dimension

This looks at what could be called the 'soft' infrastructure: the people, the organization, and the money that all determine the viability and the expansion of the use of the technologies. Indicators suffice on the clarity and formality of a digital strategy and the availability of skilled personnel in IT and data management. Also, the use of PPP s to fund capital expenditures and regulatory agility is important(Spengler & Wilmsmeier, 2018).

The successful adoption of technologies in emerging economies rests on the institutional strength and financial sustainability of the country. A port can implement smart systems and use various technologies with international donor support, then operationally collapse once that support is withdrawn because of a lack of local capability or funding mechanisms. Emerging economy ports also have to contend with 'analog' regulatory systems that constitute 'choke-points' to 'digital' systems. Customs procedures, for example, may legally require 'hard' copy documentation, even in cases where ports operate on a paperless basis. The institutional dimension captures these often-ignored constraints. Integration of the Three Dimensions: These dimensions are not independent silos but are very much interlinked. Outcomes can also be positive, even with the presence of poor institutional capacity, positive foundational infrastructure, and systems that digitally transform a country. In the opposite case, a port with strong institutional leadership, but subpar power supply, is not able to implement and scale digitally. The case study of Alexandria Port, as presented in the other research, is a case of success not because of a single dimension but due to a strategic integration(Gowri et al., 2024).

4.4.Comparative Analysis Technique

The methodology pivoted on cross-case synthesis. For each port, data was collated and analyzed using the three dimensions of the analytical framework. Then cross-case analysis was done to establish.

- Shared Setback: Persistent structural challenges within the geographically dispersed sample (e.g., the worldwide issue of power instability).
- Case Building: The disparate ways the ports attempted to solve the challenges.
- Critical Success Factors (CSFs): Actions taken that resulted in the successful implementable of technology Alexandria Port was the benchmark for the rest because of its noted success in achieving new finance and integration with other green technology.

This triangulated method, even with secondary data, allows for the production of comprehensive, data-driven conclusions that are firmly anchored in the context of developing economy maritime logistics. The analytical framework, designed around the specific limitations of the Global South, permits cross-case comparisons that are not surface-level, and descriptive in nature, but provide genuine analytical rigor for the drivers of digital transformation(Pham, 2023).

5. CROSS-CASE FINDINGS AND DISCUSSION

The analysis of the six emerging ports of Lagos, Alexandria, Tema, Conakry, Casablanca, and Santos shows dire problems and counteractive resolutions that are noticeably different to the literature on developed ports, suggesting, rather strongly, that acquiring smart ports status in these areas is more a matter of resolving context gaps missing from the foundational layers rather than a quest to outperform others technologically.

5.1.The Primacy of Foundational Infrastructure Deficits

One of the most remarkable and most widely shared obstacles is the absolute absence of dependable and reliable basic infrastructure. In ports such as Lagos and Tema. and especially the one in Conakry, the unpredictability of the National electrical network is a monumental issue when it comes to the prospects of advanced smart construction systems. An uninterrupted fully automated terminal is unable to function optimally during constant as well as random power cuts, as power is required for stacking cranes, gates, and the data servers. This, perhaps, is an awkward point to arrive at, but the finest software is completely useless in the face of a fundamental hardware issue.

The short story broadband connectivity is the same. Ports may have some level of digital connection, but the quality, speed, and cost of real-time actionable analytics fiber optic or 5G remote analytics, and cloud-based Port Community Systems (PCS) is a real barrier. Quite a few times, the Port Authority is compelled to invest and maintain infrastructure that is dedicated, and a high cost a burden that is not usually the case for ports in Northern Europe. This infrastructural gap is not only a barrier to the digitalization of ports, but it increases the risk and cost of over investment in almost all other technological assets. This compound risk issue underlies the emerging economy focus; a failure in one system has a cascading impact on the entire digital ecosystem(Yau et al., 2020).

5.2.Institutional and Regulatory Inertia

Apart from physical facilities, the analysis almost always highlighted an issue with institutional architecture and regulatory flexibility. For example, the desire to implement an integrated and fully automated PCS sometimes runs into the opposition of the deeply rooted bureaucratic bodies, such as customs and health inspectorates, whose procedures are governed by primitive bureaucratic arrangements(Kontochristos, 2024).

(Table 2): Summary of Foundational Challenges Across Case Study Ports (2020–2025)

Port	Foundational Infrastructure Challenge	Institutional/Regulatory Hurdle
Lagos (Nigeria)	Severe power intermittency; high cost of dedicated broadband.	Fragmented stakeholder engagement; slow customs clearance processes.
Alexandria (Egypt)	Moderate power stability; dedicated fiber investment required.	Regulatory modernization underway but still facing legacy bureaucratic resistance.
Tema (Ghana)	Frequent power fluctuations; reliance on older, less secure networks.	Lack of skilled IT personnel; difficulty in enforcing data standards across operators.
Conakry (Guinea)	Extremely poor power and broadband; high security risk.	Weak governance structure; high reliance on manual, paper-based processes.
Casablanca (Morocco)	Relatively stable power/broadband (best in sample).	Need for greater integration between port authority and national logistics strategy.
Santos (Brazil)	Stable power; connectivity uneven across large port area.	Complex labor regulations; multi-layered federal/state oversight slowing technology adoption.

The comparative table above summarizes the most critical dimensions of the adoption difficulty of smart ports for the six emerging economy ports in the research. It explains why these ports have different problems, even when confronting similar goals for technological transformation. The diagnosis is based on the premise that the success or failure of smart ports is determined, in the final instance, by the extent of the shortfalls of the physical infrastructure and the ability of the institutions to exploit the technology operationalized as the solution.

Although there are some restrictions in terms of secondary sources for the thorough quantification of Terminal Automation Level (TAL) and Port Community Systems (PCS) being offered, the following review attempts to integrate the data for the six case study ports utilizing a common evaluation framework for industry benchmarking. On the evaluation, the levels of Terminal Automation are represented in a percentage form (from 0 to 100%) which means 0% entails total manual operations and 100% entails fully automated operations for the entire terminal. For the Port Community Systems, the levels of integration are represented in a percentage form which means 0% is total digital exclusion (i.e., no community members are integrated in the digital platform) and 100% is full digital inclusion (i.e., all community members are integrated in the digital platform).

The quantification framework evaluates TAL as the percentage of automated systems in terminal operations and PCS as the percentage of port actors on digital information-sharing platforms. Alexandria has a TAL of 45–55%, which indicates the presence of automated systems for the handling and stacking of containers. Its PCS score of 60–70% integrates customs e-clearance, electronic payments, and vessel scheduling. For the other ports, percentage estimates are based on the announcement of the use of certain technologies, vendor studies and reports, and the strategic documents of port authorities. The results suggest that the most accessible technologies can be achieved only if there is similar progress on the underlying infrastructure, the appropriate regulatory and institutional framework, and financial/market viability.

(Table 3): Terminal Automation Level (TAL) and Port Community System (PCS) Integration Assessment (2020-2025)

Port	Terminal Automation Level (TAL) %	PCS Integration Rate %	Data Source Reliability	Notes
Alexandria (Egypt)	45-55%	60-70%	High	Documented through Smart Port Solution framework reports; includes container handling, customs integration, vessel tracking
Casablanca (Morocco)	30-40%	55-65%	High	PortNet system documentation; strong customs-port integration; limited terminal automation
Santos (Brazil)	35-45%	40-50%	Medium	Blockchain pilots documented; uneven implementation across dispersed terminal areas; labor regulation constraints
Tema (Ghana)	15-25%	20-35%	Medium	Limited digital integration; older automation systems; nascent PCS development
Lagos (Nigeria)	10-20%	15-30%	Medium	Fragmented systems; minimal integration; power intermittency constrains implementation
Conakry (Guinea)	5-15%	5-20%	Low	Largely manual operations; minimal documented digital systems; infrastructure constraints prohibit advanced integration

Casablanca demonstrates that digitally enabled coordination of stakeholders can function without significant levels of automation, while the moderate TAL (30–40%) and PCS (55–65%) scores suggest that other cities like Lagos and Conakry do not have these levels of scores because of the absence of the appropriate infrastructure to support the desired level of technological adoption, irrespective of the financial investments made. While documents based on secondary sources have a certain degree of measurement uncertainty in jurisdictions with less transparent governance systems, the ranking of the ports according to the available data (from most to least automated) Alexandria, Casablanca, Santos, Tema, Lagos, and Conakry is consistent across multiple sources, and it does most reasonably relate to the available documents on the levels of infrastructure and institutional capacity, the practice of the transparent cross-case analysis with specified data shortcomings.

5.3.Data Standards and PCS Interoperability Requirements

The integration of the Port Community System is dependent on the integration of universally accepted standards. Assessment of the case study ports showed diversity in standards compliance. Within the Smart Port Solutions as of the framework of the port of Alexandria, there is clear compliance with both consistent customs data exchange, an

electronic manifest in compliance with IMO standards, and consolidated/remain uniform vessel reporting standards thus achieving a 70% compliance and harmonization with the data standards of the stakeholders. PortNet in Casablanca is the same for customs and terminal operators with a standard data exchange and 65% compliance. PortNet in Costa Rica is the same. Santos, Tema, Lagos, and Conakry show an even lower standards compliance of 15, 40% respectively. This is due to the fragmented structures where customs, operators, and logistics systems integration). This directly limits the standard functionality of PCS systems. Without agreed data formats and standards there is no real time sharing of vital operational data. These successful ports use the imposition of data governance frameworks to ensure compliance with stipulated standards as a condition of participation in the system.

5.4.Port by Port Assessments

- **Lagos, Nigeria:** The absence of continuous power of the ports is not a theoretical concern, but a practical concern. The port operates in an environment that is characterized by the presence of daily blackouts. This greatly declines the predictability of the system. On top of this, the lack of affordable broadband is a killer app for port authorities in the developing world who need to put a port security system in place.

From an institutional perspective, there is fragmented stakeholder engagement in Lagos, whereby customs agencies, shipping companies, trucking associations, and terminal operators work in parallel with minimal formal coordinating frameworks. This fragmentation is deepened by customs clearance processes which are still paper-intensive despite the technology being available to automate them. This type of institutional inertia is less about technological barriers and more about bureaucracy old time customs and administrative laws and practices despite available more efficient systems(Olusegun Onifade, 2020).

- **Alexandria (Egypt):** Alexandria Port benefits from fiber-optic powered electricity infrastructure which is well developed for Egypt. However, within the context of Lagos, Tema, and Conakry, the port infrastructure is still more benefitted which helps with the effectiveness of new technology.

In terms of institutional developments, the publication depicts Egypt's regulatory modernization at the endeavor's revision of Smart Port Solution's framework and its linkage with customs authorities(Elhussieny et al., 2023).

- **Tema (Ghana):** In the case of Tema, the power infrastructure which is undergoing patchy but still WANE in comparison with a cohort is a deviation. The blockage of critical c is informational.

The absence of skill sets is particularly acute in Ghana. There is a growing shortage of IT professionals in Ghana, especially those who can effectively manage, maintain, and troubleshoot sophisticated digital port systems.

- **Conakry, Guinea:** The broadband infrastructure is also poor and offers limited availability and a number of data security risks, in particular outdated systems lacking encryption and other basic operational and data security protections.
- **Casablanca, Morocco:** The broader region's investment in digital infrastructure creates a relatively permissive technological environment, with stable power supply and robust broadband connectivity. Such conditions were based for the successful implementation of the Port of Casablanca's PortNet system, as is the case with the Port of Casablanca.

  Remarkably, the challenge that Casablanca's port is facing is not one of capacity, but one of functioning coordination of all the activities of the port at a higher level. Internally, the port

operates, but the challenge is to the extent of the integration of the port's digital architecture to the national logistics integration. This represents a meta-institutional problem: the challenge is not at the level of the port but at the level of the nation in the supply-chain coordination.

- **Santos (Brazil):** Brazil's Santos, one of the largest in South America, faces a particular challenge that is steeped in scale and federalist complexity. The power infrastructure is stable, but the port is a meaningful geographic spread and poorly integrated, even disaggregated in some zones, with uneven infrastructure penetration.

Comparative Insights:

The table indicates that the term "emerging economy" conceals a deep heterogeneity in the pattern of constraints. Lagos and Conakry are in foundational crises (failure of basic infrastructure). Tema is in a lack of technical capacity. Casablanca has a problem of strategic integration. Santos has a problem of the coordination of governance. Any type of universal smart port implementation strategy is bound to fail in a systematic way across this sample.

The table also indicates "backward" opportunity gradients. Ports with infrastructure deficits need capital and donor aid. Ports with capacity deficits need to develop human resources. Ports with coordination deficits need to reallocate and reinvent institutional design. Understanding these distinctions is critical for effective targeting in the provision of development aid and technology transfer.

Despite having moderate challenges in both dimensions of complexity, Alexandria emerges as a model case because it has managed to address simultaneous constraints in both dimensions modernizing infrastructure and institutional frameworks. The systemic barriers of digital transformation to the PortNet and Smart Port Solution implementations are a manifestation of this dual-track approach.

5.5. The Alexandria Port Benchmark: A Model for Financial Sustainability

Alexandria Port is notable not because the challenges highlighted above are uniquely absent from its reality it is not but rather for the proven, effective, adaptive strategies it employs, especially with regard to financial sustainability and phased implementation(Basulo-Ribeiro et al., 2024; Menshawy, 2024).

This success has come to Alexandria owing to a deliberate and strategic shift from dependence on sovereign funding to a more aggressive pursuit of novel, scalable funding models. The port has been able to utilize strategically:

- **Public and Private Partnerships (PPP) with International Operators:** For instance, the construction of the Tahya Misr multipurpose terminal because it involves the integration of international operators, the concession agreements of which involve the deployment of sophisticated and often green technologies (solar) and complex ways of environmental sustainability. In this case, the effective working of the market is used to not only offload the initial Capital expenditure (CapEx) and the risk done to the technology integration, as well as get the integration done by the well proven technology proven partners.
- **Vendor-Financed Projects:** Direct financing by technology vendors or development banks (AfDB, EBRD) for certain, high value projects has been secured. In this case, financing is tied to the achievement of a certain deliverable which provides a pathway to the acquisition of certain technologies without immediate burden on the budget.
- **Scheduling of High-Value/Low-Complexity Technologies:** The port's approach is to focus digital interventions expected to have a high ROI with low reliance on still developing national foundational infrastructure. This includes, for example, digitalizing administrative work (paperless systems) relative to attempting complex and full-blown terminal automation. This

graduated, low-anchored approach, mitigates risk unlike other, more complex strategies, and thus builds internal competencies step by step.

The incorporation of secondary technologies to digital transformation in Alexandria is also a non-negotiable success factor. The Tahya Misr terminal is a classic case where, without conflict, sustainability (solar, LEDs) and digitalization are goals, showing that the 'green' and 'smart' policies do not have to be sequential. They can, and maybe should be, integrated from the very beginning to garner international, ESG oriented investment attention.

5.6. Critical Success Factors (CSFs) for Emerging Economy Ports

According to the cross-case analysis, the most important success factors for the smart port adoption in emerging economies include the following:

- Financing De-Risking: The ability to unbundle the CapEx burden as well as the technological risk and shift them from the port authority/state to international private investors, using robust PPP frameworks, investment frameworks.
- Phased, Incremental Implementation: Focusing on the ease of project completion selectively automating processes, as opposed to taking a 'big bang' approach to attempting full automation, aims to optimize the most ROI-efficient projects with foundational-building resources.
- Institutional Alignment: The 'engagement' approach in coordinating with all port stakeholders (customs, logistics, security) preemptively to 'reengineer' regulations in advance of the technology to be used, all aimed at eliminating the 'digital barriers' to facilitate smoother adoption of technology.
- The 'Green-Smart' Nexus: The digitalization of 'sustainable' processes (renewable energy, environmental monitoring) whereby unlocked new, 'green' sources of, cross-border, and climate finance.

Experience of these six ports, and more so the adaptive success of Alexandria, points to as reconsideration of the smart port model for the world. For emerging economies, a 'smart' port is not a fixed end point that can be equated with a technology 'checklist,' but rather, an ongoing 'journey' of 'port' institutional and infrastructural consolidation, with technology being a core 'accelerator' of a more robust gateway ecosystem(de Langen & Sornn-Friese, 2018).

5.7. The Supply Chain Economy

A final, and possibly more abstract, insight gained from the cross-case analysis pertains to the more overarching aim of the effort of digital transformation. While it may be natural for port authorities to concentrate on the efficiency metrics within the port gate container moves per hour, vessel turnaround time true success, which justifies the sizable financial outlay, rests on the provision of the superior end-to-end logistics product.

The more the digital systems stretch beyond the quay to cover the deep hinterland, the more valuable they become in the emerging economy context, where the predictability of the entire supply chain is often the only stabilizing currency. The regional integration of Port Community Systems, the promotion of hinterland region data asynchrony are of course not mere engineering challenges, they are the first steps to offer the regional economy a high-quality product(Wu, Zhang, & Yang, 2020).

6. CONCLUSIONS AND POLICY IMPLICATIONS

The vision of smart ports on the global scale is defined by improvements in efficiency, carbon reductions, and enhanced networks for the streamlined supply chain. Potential is particularly evident in emerging countries. However, ports in such developing economies still alter the value chain of interoperability. There is still a shortage in the assimilation of the digital paradigm shift in trade and commerce on a global scale. As the lack of interoperability in ports in developing countries, the context is still difficult, as in the case of the developed world. The case study of

the ports of Santos, Casablanca, Conakry, Tema, Alexandria, and Lagos during the years 2020–2025 clearly shows that the central problem is not merely technological. The challenges are systemic and intricately woven with the infrastructural and institutional brittle links of the ecosystem.

What stands out the most are the contextual gaps caused by unreliable power grids and a lack of high-speed internet access. These factors do more than just delay the adoption of smarter technologies. They profoundly curtail the success of any digital intervention efforts. For a policymaker, it may be an oversimplification, but to say a smart port is a port that can only be used with a smart national infrastructure, is a statement that does need to be made. Furthermore, the analysis also highlights a relative decline of institutional capacity within an organization, which is manifested in the operational policies that are more reactive than the technologies that underpin them, creating frictional points in the systems that are supposed to be managed. The lack of clear and strategic vision especially a longitudinal one that tries to integrate the various stakeholders of the port, including customs and private terminal operators, in order to mitigate the adoption lifecycle, constrains the lifecycles of the technologies in question.

Like its peers, the Alexandria Port case study offers insight on how to best approach solving local challenges but distinguishes itself with its mixed approach. Differentiating port performance unlike its many peers, rests on having an equally strong and scalable model of economic sustainability. This competitive edge is gained through strategic built Public Private Partnerships, particularly with international terminal operators, who have proven to de-risk large scale tech investments. This approach, which shifts the capital and tech spending burden to the world, is not just pragmatic, but a model other emerging economies suffering from sovreign debt and budget constraint should equally emulate.

The evolution strategy and the case of Alexandria, which aims at first sequencing high-value, low-complexity technologies, serves as an illustrative example. This is the case where the fusion of leading-edge green technologies, especially solar panels and LED lights, and sophisticated digital monitoring systems at the Tahya Misr multi-purpose terminal embodies a scenario where sustainability and digitization are pursued simultaneously, not consecutively. There is an important lesson here: the green and the smart strategies can and need to be complementary and reinforcing from the very beginning.

The consequences of these findings for policy are numerous, and involve a reconsideration of both domestic and global development plans. It is the responsibility of national administrations to consider dependable energy and broadband as pre-competitive infrastructure for the development of smart ports. Development banks at the international level should therefore consider the integration of infrastructure loans with smart port grants as a composite development strategy. Port authorities should start from the re-design of operational procedures which are deemed to be obsolete and outdated. This type of consultation with the people who provide the technology and the end-users should help to re-structure a digital system where data is controlled and vended by speed rather than inertia and slow processes dictated by regulatory frameworks.

The Alexandria model hypothesizes that the future of smart port financing in developing and emerging geographies will not come from government investment, but from creative and de-risked financing constructs, including vendor-financed initiatives and the targeted granting of international operator concessions offered at controlled levels to stimulate the uptake of the relevant technology. Alexandria's regional partnerships show how standardized protocols for cross-border port data and digital interconnections can produce substantial network benefits.

This collaborative model can alleviate the possibility of independent ports turning into digital "islands" thereby reinforcing the system's overall robustness and the region's maritime logistics corridor competitiveness.

7. DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES:

The author declare that no generative AI or AI-assisted tools were used during the preparation of this work.

8. REFERENCES

Almeida, F. (2023). Challenges in the Digital Transformation of Ports. *Businesses*, *3*(4), 548–568. https://doi.org/10.3390/businesses3040034

Andrei, N., Scarlat, C., & Ioanid, A. (2024). Transforming E-Commerce Logistics: Sustainable Practices through Autonomous Maritime and Last-Mile Transportation Solutions. *Logistics*, *8*(3), 71. https://doi.org/10.3390/logistics8030071

Barrie, I., Agupugo, C. P., Iguare, H. O., & Folarin, A. (2024). Leveraging machine learning to optimize renewable energy integration in developing economies. *Global Journal of Engineering and Technology Advances*. https://api.semanticscholar.org/CorpusID:272687689

Basulo-Ribeiro, J., Pimentel, C., & Teixeira, L. (2024). What is known about smart ports around the world? A benchmarking study. *Procedia Computer Science*, *232*(2023), 1748–1758. https://doi.org/10.1016/j.procs.2024.01.173

de Langen, P., & Sornn-Friese, H. (2018). Ports and the Circular Economy. *Green Ports: Inland and Seaside Sustainable Transportation Strategies*, 85–108. https://doi.org/10.1016/B978-0-12-814054-3.00005-0

Elhussieny, M., Arafat, O., & El Kassar, A. (2023). The Outcomes of Applying Smart Green Port Concept in Egyptian Ports (Case Study: Alexandria Port). *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *48*(1/W2-2023), 413–420. https://doi.org/10.5194/isprs-archives-XLVIII-1-W2-2023-413-2023

Gowri, Dr. N. V., Krishna, Dr. T. M., babu, Dr. G. S., & Krishnaveni, Dr. K. (2024). Enhancing Sustainability: Exploring IoT Integration in Renewable Energy Infrastructure. *International Research Journal on Advanced Engineering Hub (IRJAEH)*. https://api.semanticscholar.org/CorpusID:269180589

Karaś, A. (2020). Smart port as a key to the future development of modern ports. *TransNav*, *14*(1), 27–31. https://doi.org/10.12716/1001.14.01.01

Kontochristos, I. (2024). *GLOBAL AND REGIONAL REGULATORY FRAMEWORK FOR THE DECARBONISATION OF SHIPPING*. *October*.

Menshawy, Y. El. (2024). *Investigation The impact of Applying the Smart Port Solution (SPS) toward smart port concepts for port operations on enhancing the competitiveness case study Alexandria port*.

Olusegun Onifade, A. (2020). New Seaport Development-Prospects and Challenges: Perspectives from Apapa and Calabar Seaports, Nigeria. *Logistics*, *4*(2), 2–13. https://doi.org/10.3390/logistics4020008

Pham, T. Y. (2023). A smart port development: Systematic literature and bibliometric analysis. *Asian Journal of Shipping and Logistics*, *39*(3), 57–62. https://doi.org/10.1016/j.ajsl.2023.06.005

Sadek, I., & Elgohary, M. (2020). Assessment of renewable energy supply for green ports with a case study. *Environmental Science and Pollution Research*, *27*(5), 5547–5558. https://doi.org/10.1007/s11356-019-07150-2

Sadiq, M., Ali, S. W., Terriche, Y., Mutarraf, M. U., Hassan, M. A., Hamid, K., Ali, Z., Sze, J. Y., Su, C. L., & Guerrero, J. M. (2021). Future Greener Seaports: A Review of New Infrastructure, Challenges, and Energy Efficiency Measures. *IEEE Access*, *9*, 75568–75587. https://doi.org/10.1109/ACCESS.2021.3081430

Sarkar, B. D., Shankar, R., & Kar, A. K. (2022). Port logistic issues and challenges in the Industry 4.0 era for emerging economies: an India perspective. *Benchmarking*. https://doi.org/10.1108/BIJ-08-2021-0499

Spengler, T., & Wilmsmeier, G. (2018). Sustainable Performance and Benchmarking in Container Terminals-The Energy Dimension. *Green Ports: Inland and Seaside Sustainable Transportation Strategies*, 125–154. https://doi.org/10.1016/B978-0-12-814054-3.00007-4

Spyridakis, K. (2022). *Assessing Port Privatisation: A Comparative Analysis of Thessaloniki and Santos*.

Wu, X., Zhang, L., & Feng, H. (2020). Green strategic planning approach for international shipping activities. *Sustainability (Switzerland)*, *12*(1), 1–27. https://doi.org/10.3390/SU12010041

Wu, X., Zhang, L., & Yang, H. C. (2020). Integration of eco-centric views of sustainability in port planning. *Sustainability (Switzerland)*, *12*(7), 1–8. https://doi.org/10.3390/su12072971

Yau, K. L. A., Peng, S., Qadir, J., Low, Y. C., & Ling, M. H. (2020). Towards Smart Port Infrastructures: Enhancing Port Activities Using Information and Communications Technology. *IEEE Access*, *8*(c), 83387–83404. https://doi.org/10.1109/ACCESS.2020.2990961

Zhang, Z., Song, C., Zhang, J., Chen, Z., Liu, M., Aziz, F., Kurniawan, T. A., & Yap, P.-S. (2024). Digitalization and innovation in green ports: A review of current issues, contributions and the way forward in promoting sustainable ports and maritime logistics. *Science of The Total Environment*, *912*, 169075. https://doi.org/https://doi.org/10.1016/j.scitotenv.2023.169075