

ISRG Journal of Economics, Business & Management (ISRGJEBM)



ISRG PUBLISHERS

Abbreviated Key Title: Isrg J Econ Bus Manag

ISSN: 2584-0916 (Online)

Journal homepage: <https://isrgpublishers.com/isrgjebm/>

Volume – IV Issue - III (May-June) 2026

Frequency: Bimonthly



Towards Sustainable Smart Ports: An Intelligent Technology and Governance Framework for Maritime Systems

Dr. Ziad Abou Daher, Ph.D.^{1*}, Dr. Elie Mina, DBA², Assist. Prof. Dr. sc. Saša Petar, Ph.D.³

¹ Al-Imam Al-Ouzai University

² Beirut Arab University Beirut, Lebanon

³ University North Koprivnica, Croatia

| Received: 02.05.2026 | Accepted: 06.05.2026 | Published: 12.05.2026

*Corresponding author: Dr. Ziad Abou Daher, Ph.D.

Abstract

Background: Ports are evolving from cargo-handling facilities into strategic logistics platforms that are expected to deliver speed, reliability, transparency, and environmental responsibility. Aim: This article examines how intelligent technologies can support the transition toward sustainable smart ports and proposes an integrated governance framework for port authorities and operators. Methodology: The study applies an integrative qualitative literature review supported by selected international port practices. Findings: The proposed Sustainable Smart Port Intelligence Framework (SSPIF) connects IoT sensing, digital connectivity, data governance, AI-enabled analytics, blockchain-supported trust, digital twin simulation, cybersecurity, and sustainability performance management. The article also introduces a maturity roadmap and a Sustainable Port Performance Score to help managers assess whether digital investments create balanced operational, environmental, resilience, and stakeholder value. Conclusion: The article argues that a sustainable smart port cannot be achieved through technology alone. It requires reliable data, institutional coordination, skilled users, cyber resilience, sound regulation, and a clear link between digital intelligence and public value.

Keywords: artificial intelligence, blockchain, digital twin, maritime digitalization, port governance, sustainable smart ports.

1. Introduction

Maritime transport remains a backbone of international trade, and ports are the gateways through which cargo, information, capital and regulatory control are coordinated. Recent maritime reviews continue to show the strategic role of ports in global trade and supply-chain resilience (United Nations Conference on Trade and

Development, 2024). As trade volumes increase and supply chains become more time-sensitive, ports are expected to reduce congestion, accelerate vessel and truck turnaround, maintain security, comply with environmental expectations, and serve a wide range of public and private stakeholders. The traditional

model, which relies on fragmented systems and manual coordination among terminal operators, customs authorities, shipping lines, truckers, freight forwarders and logistics providers, is increasingly unable to meet these demands.

The smart port concept has developed as a response to this changing environment. In simple terms, a smart port uses digital technologies to connect physical assets, administrative processes, cargo flows, energy systems, vehicles, vessels, and people in near real time. In practice, this may include IoT sensors, automatic identification systems, optical character recognition at gates, private 5G networks, automated equipment, big data platforms, AI-supported planning tools, blockchain-based documentation, and digital twins. Yet the most successful smart-port strategies are not only about installing advanced equipment. They connect operational efficiency with sustainability, resilience, cyber-risk management, and public value.

The environmental dimension gives this transition particular urgency. Ports generate or influence emissions through vessel waiting time, cargo-handling equipment, truck queues, warehouses, lighting, refrigerated storage and other energy-intensive activities. Climate events, geopolitical shocks and congestion also affect port performance and raise costs for the wider economy. At the same time, international maritime policy is pushing the sector toward decarbonization, while recent port-performance work highlights vessel time in port as a key indicator of logistics efficiency (International Maritime Organization, 2023; World Bank & S&P Global Market Intelligence, 2024). Smart-port transformation is therefore not only a technical issue for IT departments. It is also a matter of management, environmental policy, national competitiveness and public administration.

Although smart-port research has expanded, a practical implementation gap remains. Existing studies often describe the potential of IoT, AI, blockchain, big data, and digital twins, but they less frequently show how these tools can be combined, sequenced, governed, and evaluated within the daily responsibilities of a port authority. This article addresses that gap through the Sustainable Smart Port Intelligence Framework (SSPIF). The guiding research question is: How can intelligent technologies be organized into an integrated framework that helps ports become more efficient, sustainable, and resilient?

The article offers three contributions. First, it updates the smart-port discussion by drawing on recent work related to port performance, digitalization, sustainability, and maritime decarbonization. Second, it proposes a layered framework that turns separate technological applications into an implementable management architecture. Third, it introduces a maturity roadmap and a Sustainable Port Performance Score that can help port authorities and private operators prioritize investments and monitor progress over time.

2. Literature Review

2.1 From traditional ports to smart port ecosystems

Port performance has traditionally been discussed through indicators such as throughput, berth productivity, storage capacity, and cost efficiency. These measures remain essential, but they do not fully capture the way ports now operate. A modern port is a connected ecosystem that brings together cargo, vessels, inland transport, public authorities, port-community systems, security actors, energy users, and surrounding communities. The shift toward fifth-generation ports reflects this broader understanding:

value is created not only by physical capacity, but also by integration, knowledge, coordination, and collaboration across the supply chain.

Digital transformation gives this broader view a practical form. It improves visibility across vessel calls, yard activity, gate movements, cargo status, energy consumption, environmental monitoring, and regulatory procedures. Heilig, Lalla-Ruiz, and Voss (2017) emphasize that port digitalization depends on structured information exchange and stakeholder incentives. Li et al. (2023) also show that the smart-port literature has moved beyond automation toward resilience, sustainability, governance, and data-driven decision-making. This development supports the argument that smart ports should be studied as both technological and managerial systems.

2.2 Sustainability and decarbonization pressure

Sustainability has moved from a secondary concern to a central driver of port transformation. Ports face pressure to reduce greenhouse gas emissions, air pollution, noise, congestion, and resource waste while preserving trade competitiveness. Energy management, shore-side electricity, electrified cargo-handling equipment, renewable energy, low-emission trucks, circular waste systems, and environmental monitoring are becoming part of port strategy. Acciaro, Ghiara, and Cusano (2014) underline the growing role of port authorities in energy management, while recent studies increasingly connect smart-port investment with measurable environmental and social outcomes.

International maritime policy reinforces this agenda. The 2023 IMO GHG Strategy aims for net-zero greenhouse gas emissions from international shipping by or around 2050 and includes interim ambitions for 2030 and 2040 (International Maritime Organization, 2023). Although ports are not the only actors responsible for shipping emissions, they strongly influence the conditions that make low-carbon shipping possible. They affect vessel waiting time, bunkering infrastructure, shore power, hinterland connectivity and the quality of operational data. For that reason, a sustainable smart port must combine operational optimization with support for the broader energy transition.

2.3 Intelligent technologies enabling sustainable smart ports

IoT provides the first layer of visibility. Sensors, cameras, radio-frequency identification, automatic identification system data, energy meters, weather stations, and connected equipment allow the port to observe what is happening across its physical environment. When these data sources are integrated into a port community system or operational data platform, managers can follow congestion, equipment condition, cargo location, environmental indicators, and safety risks with far greater accuracy.

AI and big data analytics add intelligence to that visibility. They can improve estimated time of arrival forecasts, berth allocation, yard planning, truck appointment systems, crane scheduling, predictive maintenance, anomaly detection, and environmental forecasting. Their usefulness, however, depends on the quality of the underlying data and on clear rules for ownership, access, model explainability, and cybersecurity.

Blockchain can support trust in situations where several actors need to share records or validate transactions. In port settings, it may be used for cargo documentation, customs records, certificates of origin, emission records, waste disposal certificates, and

contractual commitments. Its practical value is not simply that it is a new technology; it is that it can reduce information asymmetry, improve auditability, and make inter-organizational processes more transparent.

Digital twin technology brings a simulation and optimization capability to the port. A digital twin is a dynamic virtual representation of port assets and processes, supported by real-time or near-real-time data. It can model vessel arrivals, berth allocation, yard congestion, gate traffic, equipment maintenance, weather disruption, and energy demand. This makes it useful not only for daily planning, but also for testing sustainability and resilience scenarios before decisions are implemented in the physical port.

Cybersecurity must be treated as a foundation of the whole model rather than as a separate technical add-on. As ports become more connected, they also become more exposed to threats affecting operational technology, customs systems, terminal operating systems, cargo documentation, surveillance systems, and port-community platforms. A sustainable smart port therefore requires cybersecurity governance, access control, incident response, data classification, vendor-risk management, and business continuity planning.

2.4 Research gap

The reviewed literature shows substantial progress in defining smart ports and identifying their enabling technologies. However, three issues still require closer attention. First, many contributions examine IoT, AI, blockchain, and digital twins as separate tools, whereas port managers need a coherent architecture that explains how these tools work together. Second, sustainability is often treated as a general objective rather than translated into KPIs, investment priorities, and governance responsibilities. Third, developing and medium-sized ports need a staged roadmap that reflects financial, institutional, and technical readiness instead of simply replicating models used by the most advanced global ports.

Previous scholarship has already examined smart-port technologies, sustainability metrics, and performance indexes; therefore, the contribution of this article is not presented as a first attempt to measure smart ports. For instance, Othman, El-gazzar, and Knez (2022) developed a sustainable smart seaport index that connects smart-port pillars with sustainability performance across operational, environmental, energy-related, safety/security, and workforce dimensions. Building on this stream of research, the present article shifts the focus from index design alone to a broader governance-oriented framework that connects intelligent technologies, cybersecurity, stakeholder coordination, maturity planning, and sustainability performance measurement for practical port transformation.

The SSPIF responds to these issues by linking technology layers with governance roles, maturity levels, sustainability indicators, and implementation priorities. This positioning makes the

framework relevant to economics, business, management, logistics, environmental management, information management, and port administration. It also builds on recent contributions on smart-port and sustainable smart-port indexes and success factors (Molavi, Lim, & Race, 2020; Othman, El-gazzar, & Knez, 2022; Hsu, Chou, & Ding, 2023), systematic evidence on smart-port sustainability (Dağistan, Atalay, Aydın Ünal, & Aydın, 2025), and practice-based studies of smart-port ecosystems such as Tianjin and Barcelona (Henríquez, de Osés, & Marín, 2022; Liu, Lai, Wong, & Xin, 2025).

3. Methodology

This study uses a qualitative conceptual research design based on an integrative literature review. Its purpose is not to test a statistical hypothesis, but to synthesize academic and institutional knowledge into a practical framework for port authorities, policymakers, operators, and future researchers. This approach is appropriate because smart-port transformation sits at the intersection of operations management, information systems, environmental management, supply-chain governance, and public policy.

The review was organized in four stages. The first stage identified the main themes in the smart-port literature, including IoT, AI, big data, blockchain, digital twins, sustainability, and international port practices. The second stage incorporated recent academic and institutional references to strengthen the evidence base. The third stage grouped the literature into five analytical categories: operational efficiency, environmental performance, data governance, resilience, and stakeholder coordination. The final stage translated these categories into the SSPIF by mapping technologies and governance mechanisms to practical port-management functions.

Selected international port practices are used as illustrative cases. They are not presented as a statistical sample, but as examples of how different ports apply intelligent technologies according to their own governance models, commercial priorities, and environmental pressures. This is consistent with conceptual management research, where the purpose is to build a framework, clarify relationships, and derive practical implications.

4. Proposed Framework: Sustainable Smart Port Intelligence Framework (SSPIF)

The SSPIF is designed as a layered model that helps ports move from isolated digital projects toward coordinated sustainability intelligence. Its logic is that operational data should first be captured from physical port activities, then exchanged through trusted and secure platforms, analyzed through AI and simulation tools, and finally translated into measurable business and sustainability outcomes. The framework contains six layers, shown in Figure 1.

Sustainable Smart Port Intelligence Framework (SSPIF)		
<i>From operational sensing to measurable business and sustainability value</i>		
Governance Cybersecurity Standards Stakeholder Trust	L6 Layer 6 - Sustainability and Business Value Carbon, energy, waiting-time, safety, resilience and service-quality KPIs	Operational Efficiency
	L5 Layer 5 - Digital Twin and Scenario Simulation Virtual port model for berth, yard, gate, energy, disruption and investment scenarios	Environmental

	L4 Layer 4 - AI and Optimization Intelligence Forecasting, scheduling, predictive maintenance, anomaly detection and decision support	Performance Resilience
	L3 Layer 3 - Data Governance and Trusted Exchange Port community system, APIs, blockchain records, cybersecurity, access control and standards	
	L2 Layer 2 - Connectivity and Edge Processing Private 5G, Wi-Fi, edge computing, secure networks and low-latency integration	
	L1 Layer 1 - Physical Sensing and Operational Assets IoT sensors, AIS, RFID, OCR gates, cameras, cranes, trucks, vessels, meters and weather stations	
Core logic: capture reliable data -> exchange securely -> analyze intelligently -> simulate decisions -> measure impact. Designed for phased implementation by port authorities and terminal operators.		

Figure 1. Sustainable Smart Port Intelligence Framework (SSPIF).

4.1 Framework layers and functions

The six layers depend on one another. A port cannot use a reliable digital twin if it lacks accurate sensing and interoperable data. AI tools will also produce weak recommendations if the data are incomplete, delayed, inaccessible, or poorly governed. Table 1 summarizes how each layer contributes to port management and sustainability performance.

SSPIF layer	Main technologies	Management function	Sustainability contribution
Physical sensing	IoT, AIS, RFID, OCR, cameras, meters	Capture real-time status of cargo, assets, energy, traffic, and environment	Supports emissions tracking, safety alerts, and resource control
Connectivity and edge	5G, Wi-Fi, edge computing, secure networks	Move data reliably between assets, systems, and decision centers	Shortens information delays and enables low-latency optimization
Data governance	Port community system, APIs, blockchain, IAM, data standards	Create trusted, auditable, and interoperable information flows	Improves transparency, compliance, and stakeholder trust
AI intelligence	Machine learning, optimization, anomaly detection	Forecast demand, allocate resources, detect risks, and recommend actions	Reduces waiting time, fuel use, equipment downtime, and congestion
Digital twin	Simulation models, GIS, real-time dashboards	Test scenarios and coordinate physical and digital operations	Supports climate resilience, energy planning, and investment prioritization
Value and impact	KPI dashboards, carbon accounting, ESG reporting	Translate digital activity into measurable public and business value	Connects efficiency gains with emission reduction and social responsibility

Table 1. Operational and sustainability functions of the SSPIF layers.

4.2 The Sustainable Port Performance Score

To make the framework practical, this article proposes a Sustainable Port Performance Score (SPPS). The SPPS is informed by previous smart-port index research, particularly Othman, El-gazzar, and Knez (2022), which linked smart-port dimensions with sustainability performance. This article extends that logic by adding governance, data reliability, resilience, stakeholder adoption, and cyber-risk exposure as strategic management dimensions. The score is not intended to replace detailed operational dashboards. Rather, it serves as a strategic index that helps port authorities ask whether digital transformation is producing balanced value or only isolated technical upgrades.

The SPPS can be organized around five value components and one risk component. Operational efficiency may be assessed through vessel turnaround time, truck waiting time, berth productivity, and yard utilization. Environmental performance may be assessed

through CO₂-equivalent emissions, energy intensity, air quality, noise, and waste indicators. Data reliability can be evaluated through completeness, timeliness, and accuracy. Resilience can be evaluated through recovery time after disruptions, redundancy, and scenario readiness. Stakeholder adoption may be measured through platform participation, user satisfaction, and training completion. Cyber-risk exposure can be tracked through unresolved vulnerabilities, incident frequency, and compliance gaps.

In simplified form, the SPPS may be expressed as: $SPPS = w_1(OE) + w_2(EP) + w_3(DR) + w_4(RS) + w_5(SA) - w_6(CR)$, where OE is operational efficiency, EP is environmental performance, DR is data reliability, RS is resilience, SA is stakeholder adoption, CR is cyber-risk exposure, and w represents the weight assigned to each variable. The weights should be defined by the port authority through strategic priorities, national regulation and stakeholder consultation. A congested gateway port, for example, may give

more weight to vessel and truck waiting time, while a port close to dense residential areas may give more weight to emissions, noise and air quality.

Hypothetical weighting example. A medium-sized container port seeking to reduce congestion and emissions could assign 30% to operational efficiency, 30% to environmental performance, 15% to data reliability, 15% to resilience and 10% to stakeholder adoption, while applying cyber-risk exposure as a 10% penalty. If the normalized scores are OE = 75, EP = 60, DR = 70, RS = 65, SA = 80 and CR = 40, the SPSS would be: $0.30(75) + 0.30(60) + 0.15(70) + 0.15(65) + 0.10(80) - 0.10(40) = 64.75$ out of 100. This result would indicate moderate progress: operational performance is improving, but environmental performance and cyber-risk reduction still require management attention.

4.3 Smart Port Sustainability Control Tower

The most practical operational element of the framework is the Smart Port Sustainability Control Tower. It can be viewed as a cross-functional decision center that brings operational, environmental, cyber, and commercial data into one dashboard. Unlike a traditional operations center focused mainly on cargo movement, this control tower also tracks sustainability and resilience indicators in real time.

Such a control tower should include dashboards for vessel arrivals, berth occupancy, yard congestion, gate queues, energy consumption, equipment status, emission estimates, air quality, weather risks, cybersecurity alerts, and stakeholder service levels. AI models can recommend actions, while the digital twin can simulate their likely impact before implementation. For example, the port could compare the operational and environmental effect of changing berth allocation, activating shore power, rescheduling truck appointments, or adjusting crane deployment.

This creates a direct connection between business efficiency and public value. Faster vessel turnaround can lower logistics costs and emissions at the same time. Predictive maintenance can reduce downtime and unnecessary fuel consumption. Better truck appointment systems can ease urban congestion. Digital documentation can reduce administrative delays and corruption risks. In this way, sustainability becomes part of daily operational management rather than a separate reporting exercise prepared after the fact.

5. International Practices and Illustrative Cases

International experience shows that there is no single universal model for smart-port transformation. Each port adapts digital tools according to its size, cargo profile, governance structure, financing capacity, location, and national policy environment. Nevertheless, several useful patterns can be identified.

First, advanced ports such as Rotterdam, Singapore, Hamburg, Barcelona and Tianjin demonstrate the importance of platformbased coordination. Rotterdam is often associated with digital twin thinking, sensorbased visibility and predictive logistics. Singapore emphasizes integrated port planning, automation and coordinated maritime services. Hamburg illustrates the value of smart traffic management and portcommunity platforms (Kapkaeva, Gurzhiy, Maydanova, & Levina, 2021). Barcelona is useful for understanding business-model innovation in port digitalization (Henríquez et al., 2022), while Tianjin shows how smartport development can be studied as an ecosystem of stakeholders, cargo flows, information flows and sustainability outcomes (Liu et al., 2025).

Second, international practice suggests that digitalization produces stronger results when it is linked to a clearly defined operational problem. Examples include reducing vessel waiting time, improving gate scheduling, increasing yard visibility, managing dangerous goods, improving customs clearance, planning shore power, and predicting equipment failures. Technology introduced without a specific problem often becomes costly, fragmented, and underused.

Third, smart-port transformation increasingly depends on collaboration beyond the physical port boundary. Inland terminals, rail operators, trucking companies, customs authorities, shipping lines, freight forwarders, and municipal authorities must share information and coordinate decisions. For this reason, governance and trust are just as important as the technologies themselves.

6. Implementation Roadmap and Maturity Model

Because ports differ in readiness, the SSPIF should be implemented through a maturity roadmap rather than through one large investment. Table 2 proposes five maturity levels that can help port authorities plan realistic transformation phases.

Maturity level	Description	Priority actions	Expected outcome
Level 1 - Fragmented	Manual processes and isolated systems dominate.	Map processes, identify data owners, digitize core documents, and define KPIs.	Basic visibility of gaps and priorities.
Level 2 - Connected	Key assets and actors begin sharing operational data.	Install sensors, improve network coverage, introduce port community system, and standardize data.	Reduced information delays and better coordination.
Level 3 - Integrated	Operational, administrative, and environmental data are combined.	Create a data lake or integration platform, implement cybersecurity governance, and launch dashboards.	One shared operational picture across stakeholders.
Level 4 - Predictive	AI models and digital twins support planning and decision-making.	Deploy forecasting, predictive maintenance, simulation, and optimization tools.	Lower congestion, better asset use, and improved resilience.
Level 5 - Sustainable autonomous ecosystem	Decision support is embedded in daily operations and sustainability management.	Automate selected processes, expand shore power/renewables, use blockchain for trusted records, and continuously audit performance.	Measurable efficiency, decarbonization, and public-value gains.

Table 2. Smart-port sustainability maturity roadmap.

The roadmap suggests that ports should not start with advanced AI or digital twin investments before establishing data quality, connectivity, stakeholder governance, and cybersecurity controls. For developing economies and medium-sized ports, a realistic starting point may be the digitalization of vessel calls, gate operations, customs procedures, energy meters, and environmental monitoring. Once these foundations are stable, predictive analytics and simulation tools can be introduced with less risk.

Financing also needs careful attention. Public-private partnerships can support investment in shared platforms, shore-side electricity, renewable energy systems, sensor networks, and cybersecurity

infrastructure. However, procurement and partnership contracts should avoid vendor lock-in by requiring open standards, interoperability, data portability, clear service-level agreements, and knowledge transfer.

7. Challenges and Risk Mitigation

Smart-port transformation creates valuable opportunities, but it also introduces risks. The most common concerns relate to cost, interoperability, cyber exposure, skills, governance, and unequal distribution of benefits among stakeholders. Table 3 summarizes these challenges and proposes mitigation measures.

Challenge	Risk to transformation	Recommended mitigation
High capital and operating cost	Projects may remain at the pilot stage or become financially unsustainable.	Prioritize use cases with measurable returns, adopt phased investment, and combine public and private financing.
Legacy systems and interoperability gaps	Data may remain fragmented, weakening AI outputs and decision support.	Use APIs, data standards, integration architecture, and procurement clauses requiring interoperability.
Cybersecurity threats	Operational disruption, data loss, or safety incidents may occur.	Apply cyber governance, access control, network segmentation, incident response, and regular audits.
Weak stakeholder trust	Actors may be reluctant to share data or adopt common platforms.	Create data-sharing agreements, neutral governance, clear privacy rules, and stakeholder committees.
Skills and organizational resistance	New systems may be underused if staff are not prepared for new workflows.	Invest in training, change management, user-centered design, and operational champions.
Greenwashing risk	Digitalization may be presented as sustainability without measurable impact.	Define audited environmental KPIs and link investments to emission, energy, and congestion outcomes.

Table 3. Key challenges and mitigation measures for sustainable smart ports.

8. Managerial and Policy Implications

For port authorities, the main implication is that smart-port transformation should be managed as a portfolio of business and sustainability outcomes. A port authority should define a digital strategy, assign data ownership, establish cybersecurity governance, and require each technology project to report operational, environmental, and stakeholder value. A port that measures only throughput may overlook emissions, safety, and resilience benefits; a port that measures only environmental indicators may overlook cost and service-quality effects. Balanced measurement is therefore essential.

For private operators, the framework shows the value of participating in shared digital platforms. Terminal operators, trucking companies, shipping lines, and logistics providers benefit when data exchange reduces waiting time and uncertainty. At the same time, private actors need confidence that their data will not be used against their commercial interests. This requires neutral governance, data classification, clear rules for access and use, and practical safeguards for confidentiality.

For policymakers, smart ports should be part of national logistics, trade facilitation, climate and digital transformation strategies. Governments can support adoption through standards, incentives for low-carbon equipment, cybersecurity guidance, port-community system modernization, skills development and public-private investment. In developing economies, policy should avoid unrealistic technology leapfrogging and instead support a sequenced roadmap that begins with core digital infrastructure and reliable data, consistent with the reform-oriented guidance in port

modernization and digitalization studies (United Nations Economic and Social Commission for Asia and the Pacific, 2023; World Bank, 2020).

9. Limitations and Future Research

This article is conceptual and qualitative. It proposes a framework based on literature synthesis and illustrative international practices, but it does not empirically test the SPSS. Future research can apply the framework to one or more ports, collect operational and environmental data, and examine whether digital investments lead to measurable improvements. Comparative studies between large transshipment hubs and smaller regional ports would be particularly useful.

Future research can also refine the weights of the Sustainable Port Performance Score using multi-criteria decision-making methods such as the Analytic Hierarchy Process, the Best-Worst Method, or Delphi consultation with port experts. Cybersecurity maturity in ports is another important research area, especially where operational technology, port community systems, customs platforms, and private terminal systems interact. Researchers should also examine how smart-port benefits and costs are distributed among public authorities, private operators, workers, local communities, and end users.

10. Conclusion

The transition toward sustainable smart ports is one of the most significant changes in maritime logistics and port management. Intelligent technologies can reduce congestion, improve safety, support decarbonization, strengthen resilience, and increase

transparency. Nevertheless, technology on its own cannot deliver these outcomes. Ports also need integrated governance, trusted data exchange, cybersecurity, stakeholder adoption, and measurable sustainability indicators.

This article proposed the Sustainable Smart Port Intelligence Framework as an integrated architecture for organizing smart-port transformation. The framework links sensing, connectivity, data governance, AI, digital twin simulation, blockchain-supported trust, and sustainability measurement. It also introduces a maturity roadmap and a Sustainable Port Performance Score to help decision-makers prioritize investments and monitor results. The central argument is that a smart port becomes truly sustainable only when digital intelligence is connected to environmental performance, operational excellence, and inclusive governance.

The article is positioned within economics, business, and management because it connects port governance, logistics performance, environmental management, information management, public administration, and business strategy. It provides a practical reference for port authorities seeking to modernize responsibly and a conceptual basis for future empirical research on sustainable smart-port transformation.

Acknowledgement

Acknowledgements: The authors would like to acknowledge the academic and professional insights that supported the preparation of this article. No specific institutional or financial support influenced the analysis, findings, or conclusions of the study.

Funding: This research received no external funding.

Conflict of Interest: The authors declare no conflict of interest.

References

1. Acciaro, M., Ghiara, H., & Cusano, M. I. (2014). Energy management in seaports: A new role for port authorities. *Energy Policy*, 71, 4-12. <https://doi.org/10.1016/j.enpol.2014.04.013>
2. Dağistan, U., Atalay, M., Aydın Ünal, D., & Aydın, S. Z. (2025). Sustainability of smart ports: A systematic literature review. *SAGE Open*, 15(3). <https://doi.org/10.1177/21582440251363339>
3. Heilig, L., Lalla-Ruiz, E., & Voss, S. (2017). Digital transformation in maritime ports: Analysis and a game theoretic framework. *Netnomics*, 18(3-4), 227-254. <https://doi.org/10.1007/s11066-017-9122-x>
4. Henríquez, R., de Osés, F. X. M., & Marín, J. E. M. (2022). Technological drivers of seaports business model innovation: An exploratory case study on the Port of Barcelona. *Research in Transportation Business & Management*, 43, 100803. <https://doi.org/10.1016/j.rtbm.2021.100803>
5. Hsu, C. T., Chou, M. T., & Ding, J. F. (2023). Key factors for the success of smart ports during the post-pandemic era. *Ocean & Coastal Management*, 233, 106455. <https://doi.org/10.1016/j.ocecoaman.2022.106455>
6. International Maritime Organization. (2023). 2023 IMO strategy on reduction of GHG emissions from ships. <https://www.imo.org>
7. Kapkaeva, N., Gurzhiy, A., Maydanova, S., & Levina, A. (2021). Digital platform for maritime port ecosystem: Port of Hamburg case. *Transportation Research Procedia*, 54, 909-917. <https://doi.org/10.1016/j.trpro.2021.02.147>
8. Li, K. X., Li, M., Zhu, Y., Yuen, K. F., Tong, H., & Zhou, H. (2023). Smart port: A bibliometric review and future research directions. *Transportation Research Part E: Logistics and Transportation Review*, 174, 103098. <https://doi.org/10.1016/j.tre.2023.103098>
9. Liu, M., Lai, K.-H., Wong, C. W. Y., & Xin, X. (2025). Smart ports for sustainable shipping: Concept and practices revisited through the case study of China's Tianjin port. *Maritime Economics & Logistics*, 27, 50-95. <https://doi.org/10.1057/s41278-024-00291-3>
10. Molavi, A., Lim, G. J., & Race, B. (2020). A framework for building a smart port and smart port index. *International Journal of Sustainable Transportation*, 14(9), 686-700. <https://doi.org/10.1080/15568318.2019.1610919>
11. Notteboom, T., Pallis, A., & Rodrigue, J. P. (2021). Disruptions and resilience in global container shipping and ports. *Maritime Policy & Management*, 48(7), 879-892. <https://doi.org/10.1080/03088839.2021.1975868>
12. Othman, A., El-gazzar, S., & Knez, M. (2022). A framework for adopting a sustainable smart sea port index. *Sustainability*, 14(8), 4551. <https://doi.org/10.3390/su14084551>
13. United Nations Conference on Trade and Development. (2024). Review of maritime transport 2024. United Nations. <https://unctad.org/publication/review-maritime-transport-2024>
14. United Nations Economic and Social Commission for Asia and the Pacific. (2023). Study on smart port reforms and port digitalization. United Nations ESCAP. <https://www.unescap.org>
15. World Bank & S&P Global Market Intelligence. (2024). The container port performance index 2023: A comparable assessment of performance based on vessel time in port. World Bank. <https://doi.org/10.1596/41707>
16. World Bank. (2020). Port reform toolkit (2nd ed.). World Bank Publications.