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Smart Ports Meet Green Ports: Developing a Unified Performance Measurement Framework

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ABSTRACT

The rapid evolution of port performance, driven by technological advancements and sustainability goals, has led to the emergence of smart and green ports. This systematic review examines the integration of smart port technologies with green port practices to develop a unified performance measurement framework. Analyzing 18 peer-reviewed articles using the PRISMA protocol, the study identifies key themes such as green and smart port performance measurement, evaluation methodologies and models, and governance strategies and sustainability. Core technologies enabling this transformation include the Internet of Things (IoT), Artificial Intelligence (AI), automation, and renewable energy systems, while comprehensive Key Performance Indicators (KPIs) and Smart Performance Indicators (SPIs) are proposed to measure smart and green port performance across operational, environmental, and financial dimensions. The findings highlight the importance of integrated approaches that combine technological innovation with stakeholder engagement and policy support to enhance port competitiveness and sustainability. Challenges such as high implementation costs, legacy system integration, and regulatory complexity are discussed, alongside opportunities for operational excellence and environmental benefits. The research contributes to academic and practical understanding by proposing standardized evaluation models and implementation strategies for port authorities and policymakers.

1. Introduction.

The maritime transport sector serves as the backbone of global trade, with ports playing a pivotal role in facilitating international commerce. According to the United Nations Conference on Trade and Development (UNCTAD, 2017, December), maritime transport accounts for approximately 80% of global merchandise trade by volume and over 70% by value, underscoring the critical importance of port infrastructure in the global supply chain (Zhou, 2024).

The International Maritime Organization (IMO)emphasizes the strategic significance of ports in enabling maritime logistics and advocates for sustainable port development to meet growing trade demands while minimizing environmental impact. This dual imperative has catalyzed the evolution of traditional ports into Smart and Green Ports, representing a fundamental transformation that integrates technological innovation with environmental stewardship. The concept of Smart Ports encompasses fully automated and digitally transformed seaports that integrate innovative technologies such as 5G, Internet of Things (IoT), big data analytics, and eco-friendly systems to enhance operational efficiency and sustainability (Paraskevas et al., 2024). Port development typically progresses through four evolutionary stages: Informatization → Automation → Digitalization → Smartization, reflecting the increasing sophistication of technological integration in port operations (Makkawan, 2023); (Paraskevas, 2025). This evolution has been systematically categorized into six generations, from the basic man-

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ual operations of 1st generation ports (pre-1950s) to the conceptual 6th generation ports featuring full automation, digital twins, and real-time optimization capabilities for handling mega-vessels exceeding 50,000 Twenty-foot Equivalent Unit (TEU) as cited in table 1.

Table 1: Evolution of Ports: From 1^{st} to 6^{th} Generation.

Generation / Period	Main Characteristics	Technologies/Focus
1st Generation Pre-1950s	Basic manual operations (loading/unloading), isolated from logistics chain, no coordination among services.	Manual processes
2nd Generation 1960s–1980s	Industrialization era; ports connected to hinterland industries; emergence of service function; partial computerization.	Early ICT, basic digitalization
3rd Generation 1980s–2000s	Containerization and intermodality; emergence of logistics hubs; start of EDI systems; value-added services (warehousing, packaging, etc.).	EDI, early digital networks
4th Generation (Port 4.0) 2000s–2010s	Integration of smart technologies; ports as digital platforms; real-time data sharing; connected to global logistics networks; collaboration emphasis.	IoT, Big Data, AI, Cloud Computing, Port Community Systems
5th Generation (Smart and Sustainable Port) 2010s–Present	Customer- and community-oriented; integrates sustainability and smart systems; stakeholder co-decision; aligned with SDGs; advanced performance metrics.	AI, SWS (Single Window System), RFID, Green Energy, Data Analytics
6th Generation (Conceptual/ Future) Future-oriented	Full automation; handles mega-vessels (>50,000 TEU); seamless intermodal integration with hinterland; real-time digital twin platforms.	Robotics, Full AI, Digital Twins, Real-time Optimization, Complete Automation

Source: Belmoukari, 2023.

Concurrently, the Green Port paradigm prioritizes environmental sustainability through comprehensive practices including emission reduction (CO_2, NOx, SOx, PM), renewable energy integration (solar, wind, onshore power supply), smart pollution monitoring, waste management, and eco-friendly infrastructure development (Sadiq, 2021); (Durlik, 2024). The convergence of Smart and Green strategies is essential, where digital technologies serve as enablers for achieving environmental goals, creating a synergistic approach to port modernization (Durlik, 2024). This dual transformation is driven by multiple factors including unprecedented global trade demands requiring efficiency upgrades, stringent climate regulations such as the IMO 2020 sulfur cap and EU Green Deal mandating emission reductions, and technological disruption through artificial intelligence, IoT, and automation redefining port operations (Sadiq, 2021) (Durlik, 2024) (Zhou, 2024).

The academic discourse on smart and green ports has evolved significantly through systematic literature reviews that provide comprehensive insights into the transformation of maritime logistics infrastructure. (Paraskevas A. M., 2024) conducted a PRISMA-based systematic literature review of 39 studies, identifying four primary themes in smart port research: digitization, performance measurement, Industry 4.0 technology implementation, and emerging challenges, while emphasizing the need for integrated evaluation models and addressing gaps in governance, interoperability, and environmental impact. Similarly, (Belmoukari, 2023) analyzed 70 studies to classify smart port characteristics into seven business domains, highlighting definitional ambiguity and calling for unified understanding through mapping technological, organizational, environmental, and managerial dimensions. The sustainable maritime transport perspective has been extensively examined by (Xiao, 2024) through bibliometric analysis of 478 publications (2000-2023), identifying key research themes including trajectory prediction, clean energy, cold ironing and artificial intelligence applications, while emphasizing data security, stakeholder coordination, and economic incentives for sustainability promotion. Green port evaluation and energy infrastructure integration have gained substantial attention in recent literature, with (Fei, 2025) synthesizing 15 years of research (2009-2024) on green port evaluation methods, subjects, and indicator systems for sustainable development guidance. (Issa Zadeh, 2023) conducted a scoping review of 73 sources examining Energy Management Systems integrating IoT, AI, microgrids, and renewable energy for carbon footprint reduction, demonstrating that smart ports can optimize energy use and enhance resilience through real-time monitoring and predictive analytics, despite challenges including high costs and regulatory barriers. Contemporary research by (Alzate, 2024) employed bibliometric analysis of 204 publications, revealing China's research dominance and identifying three thematic clusters: Industry 4.0 adaptation, intelligent supply chain integration, and green port initiatives, while (Sadiq, 2021) provided comprehensive strategies for energy efficiency enhancement through renewable energy integration, technological advancements, and smart infrastructure development.

Despite the growing body of literature on smart and green ports, several research gaps remain. The existing studies primarily focus on either smart port technologies or green port sustainability practices in isolation, with limited comprehensive analysis of their integration. Furthermore, there is a lack of standardized performance measurement frameworks that can effectively evaluate both smart and green port dimensions simultaneously. The absence of unified Key Performance Indicators (KPIs) and Smart Port Indicators (SPIs) that capture the dual nature of smart and green port transformation presents a significant challenge for port authorities and policymakers seeking to implement comprehensive port modernization strategies. This study addresses these research gaps by conducting a systematic literature review that examines the intersection of smart port technologies and green port sustainability practices. The research aims to answer five main Research Questions (RQ):

RQ1: What are the main technologies enabling smart and green port transformation?

RQ2: What are the main SPIs and KPIs for measuring smart and green port performance?

RQ3: What are the main models and methodologies for evaluating smart and green port performance?

RQ4: What are the main strategies for integrating sustainability and intelligence in port operations?

RQ5: What are the opportunities and challenges faced by smart and green ports?

This study employs a systematic review methodology based on the PRISMA protocol, utilizing NVivo for comprehensive analysis of the selected literature. The research contributes to the existing body of knowledge through theoretical advancement of port performance measurement theory by examining the intersection of smart port dynamics with sustainability practices, empirical evidence of challenges and opportunities in the field, methodological integration of systematic review approaches for analyzing complex dual perspectives, practical recommendations for policymakers and industry practitioners, and policy insights for balanced stakeholder collaboration and development in port modernization initiatives.

2. Material and Methodology.

2.1. Research Objectives and Approach.

This systematic review examines how smart port performance measurement systems integrate with sustainability frameworks to enhance operational efficiency and environmental responsibility in modern port operations. The research addresses five key objectives: identifying performance indicators used in contemporary ports, analyzing evaluation models and measurement frameworks, examining implementation strategies for dual-perspective development, assessing governance structures and stakeholder coordination, and identifying opportunities and challenges in integrating technological and sustainable best practices.

2.2. Search Strategy and Database Selection.

The search strategy employed Scopus and Web of Science databases, selected for their comprehensive coverage of peer-reviewed literature in engineering, environmental science, and management fields. The Boolean search logic combined smart port concepts (”smart port,” ”digital port,” ”intelligent port”) with performance measurement and sustainability terms (”performance measurement,” ”sustainability,” ”green port,” ”environmental performance”) and indicator-related terms (”KPI,” ”metric,” ”evaluation,” ”assessment”). Search parameters were constrained to English-language publications between 2019 - 2025, focusing on peer-reviewed journal articles and book chapters to ensure academic rigor while capturing contemporary developments.

2.3. Study Selection Process.

The selection process followed systematic inclusion and exclusion criteria. Inclusion criteria required studies addressing smart port performance measurement and sustainability with empirical focus, defined indicators, and implementation strategies. Exclusion criteria eliminated systematic reviews, conference proceedings, non-peer-reviewed publications, studies with limited access, and articles outside the thematic scope. The multi-stage screening process began with 146 combined articles from both databases, reduced to 145 after duplicate removal using Zotero automated detection, Rayyan platform verification, and manual confirmation. Title and abstract screening using Rayyan platform reduced the pool to 36 articles based on relevance to key themes. Full-text assessment evaluating methodology, results, discussion, and recommendations sections resulted in 18 articles meeting all criteria for comprehensive analysis.

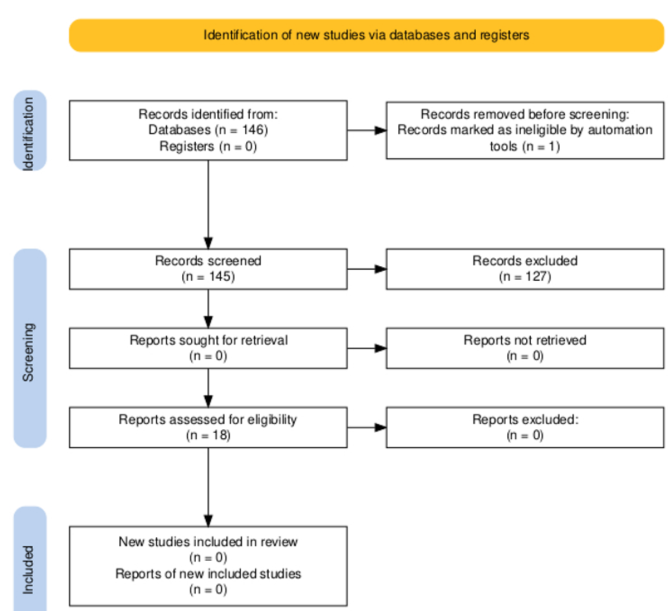
2.4. Data Extraction and Analysis Framework.

Data extraction systematically captured study characteristics, port context, technology integration, sustainability measures, performance indicators, implementation strategies, and outcomes using standardized forms supported by Zotero reference management. The analysis employed NVivo software for thematic analysis, combining inductive and deductive coding approaches around seven primary nodes: Technology (smart port technologies, digital innovations, automation systems), (SPI) Smart Port Indicators / (KPI) Key Performance Indicators, Models (evaluation frameworks, measurement models), Strategies (implementation approaches, stakeholder engagement), Governance (management structures, policy frameworks), Opportunities (integration benefits, competitive advantages), and Challenges (implementation barriers, operational difficulties).

2.5. Quality Assessment and Synthesis.

Quality assessment evaluated methodological rigor, data quality, analytical depth, practical relevance, and theoretical contribution through individual study assessment, comparative analysis, and bias identification. The synthesis approach employed narrative synthesis with thematic presentation organized by identified themes, comparative analysis across studies, and gap identification for future research. Reporting standards adhered to PRISMA guidelines ensuring transparency, reproducibility, and comprehensive coverage of all included studies as clarified Figure 1.

Figure 1: PRISMA flowchart of the research.



Source: Haddaway, 2020.

3. Results and Discussion.

3.1. RQ1.- Technologies in Smart and Green Port Development.

3.1.1. Core Technologies for Smart Port Operations.

The evolution of smart ports relies heavily on advanced automation and digitalization technologies that enhance operational efficiency and cargo handling capabilities. Automation equipment forms the backbone of modern smart port operations, encompassing Automated Guided Vehicles (AGV), Automated Stacking Cranes (ASC), Quay Cranes (QC), and robotic systems that significantly reduce manual intervention while improving precision and speed (Makkawan, 2023). These automated systems are complemented by Internet of Things (IoT) technologies that enable real-time monitoring and control of logistics operations, equipment status, energy consumption, and fuel utilization, supporting predictive maintenance and improving operational efficiency while reducing downtime (Sadiq, 2021); (Argyriou, 2023).

Big Data analytics and cloud computing platforms play crucial roles in handling large volumes of operational data, optimizing resource utilization, and supporting decision - making processes related to energy management and sustainability (Sadiq, 2021).The integration of 5G networks and high-speed communication systems facilitates real-time data transfer and seamless information exchange within port communities, while blockchain technology enhances transparency, security, and efficiency in transactions and processes related to port operations (Makkawan, 2023); (Paraskevas A. M., 2025). Artificial Intelligence (AI) applications in smart ports encompass multiple domains, including AI-driven decision-making tools for operational optimization, predictive maintenance algorithms, route optimization for vessels, and smart energy management systems (Durlik, 2024); (Paraskevas A. M., 2025). AI algorithms are particularly effective in emission reduction through fuel consumption optimization, autonomous shipping navigation, and risk assessment modeling that improves safety and decision-making processes (Durlik, 2024).

3.1.2. Green Technologies for Environmental Sustainability.

The transition toward sustainable port operations heavily relies on electrification technologies that replace traditional fossil fuel-powered equipment with electric alternatives. This includes battery-powered ferries, fully electric vessels, and electric port equipment that significantly reduce greenhouse gas emissions (Sadiq, 2021); (Gu, 2023). Onshore Power Supply (OPS) systems represent a critical green technology that provides shore-side electrical power to ships at berth, allowing vessels to switch off auxiliary engines and dramatically reduce emissions during docking periods (Sadiq, 2021); (Gu, 2023).

Energy Storage Systems (ESS) and port microgrids enable the integration of renewable energy sources and provide load leveling capabilities during peak demand periods, enhancing energy efficiency and grid stability (Sadiq, 2021). These systems work in conjunction with smart energy management technologies that optimize energy consumption patterns and facilitate the integration of renewable energy sources such as solar and wind power into port operations (Makkawan, 2023); (Argyriou, 2023). Alternative fuel technologies are gaining prominence in green port development, particularly Liquefied Natural Gas (LNG) systems that serve as cleaner fuel options for port operations and vessels, significantly reducing greenhouse gas emissions compared to traditional marine fuels (Gu, 2023). Clean energy substitution technologies encompass the incorporation of renewable energy sources and the deployment of emission-reduction systems that aim for low-carbon port operations (Gu, 2023); (Wang, 2023).

3.1.3. Digital Infrastructure and Communication Technologies.

Modern smart ports require robust digital infrastructure comprising Digital Communication Technologies (DCTs) that include interactive websites, social media platforms, and comprehensive digital communication tools that improve port competitiveness and strategic decision-making capabilities (Zhou, 2024). Terminal Operating Systems (TOS) such as Navis N4 provide centralized terminal management capabilities, while Electronic Data Interchange (EDI) systems enable automated data sharing that significantly improves vessel planning productivity (Sahraoui, 2023).

RFID and intelligent CCTV systems enhance both safety monitoring and cargo tracking capabilities, while Optical Character Recognition (OCR) technologies automate gate operations and reduce truck turnaround times (Makkawan, 2023); (Sahraoui, 2023). These technologies are integrated with real-time cargo tracking and management systems that provide comprehensive visibility across the entire supply chain.

3.1.4. Environmental Monitoring and Sustainability Technologies.

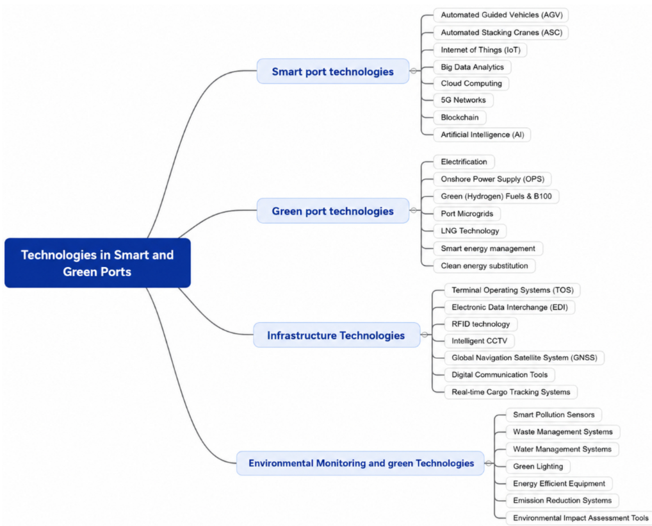
Smart ports deploy environmental monitoring technologies including smart pollution sensors for real-time monitoring of air and water quality, enabling better compliance with environmental regulations and enhancing overall sustainability efforts (Makkawan, 2023); (Durlik, 2024). Waste and water management technologies incorporate advanced systems for waste treatment, water recycling, and pollution reduction that are essential for sustainable port operations (Argyriou, 2023). Green lighting systems and energy-efficient equipment contribute to overall energy conservation efforts, while emission-reduction technologies focus on specific pollutant control systems and renewable energy integration (Gu, 2023), (Argyriou, 2023). These technologies are supported by comprehensive environmental impact assessment systems that monitor ecological effects and ensure compliance with international environmental standards - (Makkawan, 2023).

3.2. RQ2.- Key Performance Indicators (KPIs) and Smart Port Indicators (SPIs).

3.2.1. Smart Port Indicators (SPIs) Framework.

The development of comprehensive Smart Port Indicators (SPIs) represents a critical advancement in quantifying and evaluating smart port performance across multiple operational domains. A comprehensive framework identifies 19 key Smart

Figure 2: Technologies in Smart and Green Ports.



Source: Authors.

Port Indicators organized into three primary domains that capture the multifaceted nature of smart port operations (Makkawan, 2023). The Smart Port Operation Domain encompasses nine indicators focused on operational efficiency, automation, and information exchange, including the use of automation equipment for internal cargo movement, implementation of smart platforms for information exchange, deployment of IoT and RFID technologies for traffic and cargo tracking, development of terrestrial connectivity infrastructure, big data analytics for forecasting, 5G network adoption, robotics integration, real-time cargo tracking systems, and cloud computing integration (Makkawan, 2023).

Table 2: Smart Port Indicators SPIs.

Domain	SPI	Definition
Smart Port Operation Domain (9 SPIs)	Use of automation equipment for internal cargo movement	Implementation of automated systems including Automated Guided Vehicles (AGV), Automated Stacking Cranes (ASC), Quay Cranes (QC), and robots for cargo handling operations
	Implementation of smart platforms for exchanging information	Deployment of advanced platforms such as Blockchain and Cloud computing for information exchange within the port community
	Deployment of technologies for port traffic and cargo tracking	Use of IoT, RFID, and other tracking technologies for monitoring port traffic and cargo movement
	Development of terrestrial connectivity infrastructure	Enhancement of road and railway infrastructure to ensure seamless cargo movement to and from the port
	Big Data analytics for forecasting and operational planning	Application of big data analytics for predictive analysis and operational planning optimization
	Use of 5G and high-speed networks	Implementation of 5G and high-speed communication networks for real-time communication and data transfer
	Adoption of robotics for terminal operations	Integration of robotic systems for various terminal operations and cargo handling tasks
	Real-time cargo tracking and management systems	Systems that provide real-time visibility and management of cargo throughout the port operations
	Integration of cloud computing	Implementation of cloud computing solutions for scalable data management and operational support
Smart Port Environment/Energy Domain (7 SPIs)	Application of smart pollution sensors	Use of intelligent sensors for monitoring and reducing emissions from port activities
	Use of eco-friendly energy sources	Implementation of renewable and clean energy sources within port operations
	Energy-saving technologies and smart energy management systems	Deployment of technologies and systems designed to reduce energy consumption and optimize energy usage
	Waste reduction and management initiatives	Programs and systems designed to minimize waste generation and improve waste management processes
	Environmental impact assessment and control systems	Systems for evaluating and controlling the environmental impact of port operations
	Sustainable resource utilization strategies	Approaches and methods for optimizing the use of resources in an environmentally sustainable manner
	Commitment to environmental regulations and international standards	Adherence to environmental regulations and compliance with international environmental standards
Smart Port Safety / Security Domain (3 SPIs)	Safety and security upgrading using advanced technologies	Implementation of AI, Augmented Reality (AR), Virtual Reality (VR), and Digital Twin technologies for safety training and incident simulation
	Implementation of RFID and intelligent CCTV systems	Deployment of RFID technology and intelligent closed-circuit television systems for safety monitoring and surveillance
	Use of AI-powered intelligent systems for security	Implementation of AI-powered biometric access control, automatic license plate recognition systems, and RFID for enhanced security and access automation

Source: Makkawan, 2023.

The Smart Port Environment/Energy Domain comprises seven indicators that emphasize sustainability and environmental performance enhancement, incorporating smart pollution sensors for emissions monitoring, eco-friendly energy sources utilization, energy-saving technologies and smart management systems, waste reduction initiatives, environmental impact assessment systems, sustainable resource utilization strategies, and commitment to environmental regulations and international standards (Makkawan, 2023). The Smart Port Safety/Security Domain includes three indicators focusing on security protocols and safety training using advanced technologies, encompassing AI, Augmented Reality (AR), Virtual Reality (VR), and Digital Twin technologies for training and incident simulation, RFID and intelligent CCTV systems for safety monitoring, and AI-powered biometric access control systems (Makkawan, 2023).

3.2.2. *Smart and green port KPIs.*

KPIs in the port performance measurement subdivided into six main categories: operational, financial, human, sustainable development, stakeholder satisfaction and supply chain integration according to (Hajar, 2025). The indicators subdivided into two main categories:

- Qualitative indicators are subjective based on assessments that rely on human judgment. These indicators reflect perceptions and opinions are typically derived from linguistic variables such as: stakeholder satisfaction, organizational commitment to sustainability, quality of product life cycle assessments, community impact assessments, etc.

- Quantitative Indicators are numerical measures that can be quantified and compared. They usually require normalization to enable fair comparisons across different units such as: resource usage, waste reduction, recycling rates, energy consumption, emission levels, etc.

Technological development and sustainable evolution impacted by the following KPIs:

- Operational Performance Indicators.

Operational efficiency indicators form the cornerstone of smart port performance evaluation, with vessel turnaround time, dwell time, and berth utilization serving as primary metrics for assessing port productivity (Paraskevas A. M., 2025). Container throughput measurements, including TEU (Twenty-foot Equivalent Unit) handling capacity and throughput rates per meter, provide quantitative assessments of port operational capacity and efficiency (Molavi, 2019); (Zhou, 2024). Port productivity indicators encompass gate, yard, and vessel handling efficiency metrics, with studies reporting 10-75% improvements in productivity following technology implementations (Sahraoui, 2023).

Resource utilization indicators include terminal area optimization, Container Freight Station (CFS) area efficiency, berth length utilization, water depth optimization for vessel accommodation, and equipment utilization rates including quay cranes, transfer cranes, and mobile equipment deployment (Zhou, 2024). Logistics effectiveness indicators incorporate business strategy orientation, capacity planning and implementation efficiency, logistics efficiency and productivity metrics, information technology implementation levels, and supply chain collaboration effectiveness (Ricardianto, 2020). Table 3 synthetizes the main operational KPIs.

Table 3: Operational Efficiency Domain KPIs.

KPI	Definition	Reference
Vessel turnaround time	Time from vessel arrival to departure, measuring port efficiency in handling ships	Paraskevas et al. (2025); Argyriou and Tsoutsos (2023)
Berth utilization rate	Percentage of berth capacity effectively used over a given period	Paraskevas et al. (2025); Zhou and Suh (2024)
Container dwell time	Average time containers spend in the port from arrival to departure	Paraskevas et al. (2025); Sadiq et al. (2021)
Port throughput per berth	TEU or tons handled per berth, measuring berth productivity	Zhou and Suh (2024); Wang et al. (2023)
Cargo handling productivity	Number of containers or tons handled per hour	Fri et al. (2020); Ricardianto et al. (2022)
Gate processing efficiency	Average truck turnaround time at port gates	Sahraoui et al. (2023); Makkawan et al. (2023)
Yard operations efficiency	Container moves per hour in yard operations	Fri et al. (2020); Sahraoui et al. (2023)
Automation equipment usage rate	Percentage of operations using automated equipment (AGVs, ASCs, QCs)	Makkawan et al. (2023); Durlik et al. (2024)
IoT device deployment coverage	Percentage of port operations monitored by IoT devices	Makkawan et al. (2023); Paraskevas et al. (2025)
Real-time tracking system coverage	Percentage of cargo tracked in real-time using RFID, IoT technologies	Makkawan et al. (2023); Sadiq et al. (2021)
5G network coverage	Percentage of port area with 5G connectivity for real-time communication	Makkawan et al. (2023); Zhou and Suh (2024)
Cloud computing utilization	Percentage of operations using cloud platforms for data management	Makkawan et al. (2023); Sadiq et al. (2021)
Big data analytics implementation	Number of predictive analytics systems deployed for operational planning	Makkawan et al. (2023); Durlik et al. (2024)

Source: Authors.

- Financial and Economic Performance Indicators.

Financial performance indicators provide crucial insights into the economic viability and sustainability of smart port operations. Core financial metrics include revenue generation, profitability ratios, cost efficiency measures, and Return on Investment (ROI) calculations that assess the financial returns from smart port technology investments (Paraskevas et al., 2025). Operational cost indicators encompass fuel consumption costs, maintenance expenses, labor costs, and infrastructure investment requirements, with studies reporting significant cost reductions following technology implementations (Sahraoui, 20-23).

Economic impact indicators extend beyond direct port operations to include contributions to local and regional economies, employment generation, tax contributions, and overall economic multiplier effects (Argyriou, 2023); (Gu, 2023). The Liner Shipping Connectivity Index (LSCI) serves as a comprehensive economic indicator measuring how effectively ports are integrated into global shipping networks, considering factors such as number of ships, vessel container-carrying capacity, maximum vessel size, number of services, and shipping companies deployed (Nadarajan, 2023). Table 4 explains the financial KPIs .

- Safety and Security Performance Indicators.

Safety and security indicators represent critical components of comprehensive smart port performance evaluation, addressing both operational safety and cybersecurity concerns. Safety

Table 4: Financial Performance KPIs.

KPI	Definition	Reference
Operational cost per TEU	Total operational costs divided by container throughput	Paraskevas et al. (2025); Sahraoui et al. (2023)
Revenue per TEU	Total revenue divided by container throughput	Paraskevas et al. (2025); Fri et al. (2020)
Return on investment (ROI)	Financial returns on technology and infrastructure investments	Paraskevas et al. (2025); Durlik et al. (2024)
Cost efficiency	Measure of operational cost effectiveness	Paraskevas et al. (2025); Fri et al. (2020)
Asset utilization rate	Revenue generated per unit of asset value	Zhou and Suh (2024); Argyriou and Tsoutsos (2023)
Energy cost per unit	Energy expenses per TEU or per ton of cargo	Sadiq et al. (2021); Gu et al. (2023)
Maintenance cost optimization	Predictive vs. reactive maintenance cost ratio	Durlik et al. (2024); Sadiq et al. (2021)

Source: Authors.

performance indicators include nautical accident rates, compliance failures with regulations and standards, industrial incidents such as spills, fires, and explosions, and foundering incidents that assess operational safety levels (Molavi, 2019). Security investment indicators encompass financial investments in safety measures, protection infrastructure, security drill frequency, and compliance with International Ship and Port Facility Security (ISPS) requirements (Molavi, 2019). Workforce safety indicators include employee training programs in safety and anti-corruption policies, accident rates among port workers, and safety meeting and inspection frequencies that ensure comprehensive safety culture implementation (Molavi, 2019); (Gu, 2023). Cybersecurity indicators address the growing importance of digital security in smart port operations, including security breach incidents, unauthorized access attempts, and cybersecurity investment levels that protect port operations from digital threats (Makkawan, 2023).

Table 5 Summarizes the main KPIs tracking safety and security.

- Social and Human Capital Indicators.

Social performance indicators capture the human dimension of smart port operations, addressing workforce development, community engagement, and social responsibility aspects. Employee management indicators include new employee recruitment rates, employee turnover rates, gender diversity ratios, and training program effectiveness that assess human capital development (Gu, 2023). Social contribution indicators encompass social donations, employment opportunities for local communities, science and technology project investments, and social contribution per share that measure ports' broader social impact (Gu, 2023).

Stakeholder engagement indicators include stakeholder participation frequency and quality, communication effectiveness, transparency in progress reporting, and customer satisfaction metrics that assess relationship management effectiveness (Argyriou, 2023); (Gu, 2023). Community impact indicators ad-

Table 5: Safety and Security KPIs.

KPI	Definition	Reference
Accident frequency rate	Number of accidents per unit of throughput or per time period	Molavi et al. (2019); Argyriou and Tsoutsos (2023)
Security incident rate	Number of security breaches per period	Molavi et al. (2019); Makkawan et al. (2023)
CCTV coverage	Percentage of port area under intelligent surveillance	Makkawan et al. (2023); Paraskevas et al. (2025)
Safety training completion rate	Percentage of staff completing required safety training	Gu et al. (2023); Molavi et al. (2019)
AI-powered safety system deployment	Number of AI safety applications using AR, VR, Digital Twin	Makkawan et al. (2023); Paraskevas et al. (2025)
Biometric access control coverage	Percentage of access points secured with biometric systems	Makkawan et al. (2023); Paraskevas et al. (2025)
RFID tracking system coverage	Percentage of assets and personnel tracked via RFID	Makkawan et al. (2023); Sahraoui et al. (2023)
Cybersecurity incident rate	Number of cyber-attacks prevented or mitigated	Durlik et al. (2024); Paraskevas et al. (2025)
Emergency response time	Average time to respond to safety or security incidents	Argyriou and Tsoutsos (2023); Molavi et al. (2019)

Source: Authors.

dress noise level management, traffic congestion mitigation, safety and health risks for surrounding communities, and overall community well-being improvements (Argyriou, 2023). Table 6 focuses on the social and Stakeholder engagement KPIs.

Table 6: Social and Stakeholder Engagement KPIs.

KPI	Definition	Reference
Employee satisfaction index	Staff satisfaction survey results and ratings	Gu et al. (2023); Argyriou and Tsoutsos (2023)
Training hours per employee	Annual training investment per worker	Gu et al. (2023); Molavi et al. (2019)
Employee turnover rate	Percentage of staff leaving annually	Gu et al. (2023); Fri et al. (2020)
Gender diversity ratio	Percentage of female employees in workforce	Gu et al. (2023); Argyriou and Tsoutsos (2023)
Local employment creation	Number of jobs created for local community	Gu et al. (2023); Argyriou and Tsoutsos (2023)
Social investment ratio	Community investment as percentage of revenue	Gu et al. (2023); Argyriou and Tsoutsos (2023)
Customer satisfaction score	Service quality ratings from port users	Paraskevas et al. (2025); Ricardianto et al. (2022)
Stakeholder engagement level	Frequency and quality of stakeholder interactions	Argyriou and Tsoutsos (2023); Paraskevas et al. (2025)

Source: Authors.

- Environmental Sustainability Indicators.

Environmental performance indicators have gained increasing prominence in smart and green port evaluation frameworks, reflecting the growing emphasis on sustainable port development. Energy consumption indicators include total energy usage, energy consumption per unit of throughput, renewable energy utilization rates, and energy-saving rates that quantify ports' progress toward energy efficiency goals (Gu, 2023); (Argyriou, 2023). Greenhouse gas emission indicators encompass CO_2 emissions intensity, carbon footprint measurements, air pollution indices, and emission reduction capacity metrics that track environmental impact mitigation efforts (Sadiq, 2021); (Wang, 2023).

Resource utilization efficiency indicators include water consumption per unit of throughput, waste production and management efficiency, sewage discharge rates, and waste recycling rates that assess resource conservation and circular economy implementation (Gu, 2023); (Argyriou, 2023). Environmental quality monitoring indicators encompass air quality measurements, water quality parameters, noise level assessments, and habitat and biodiversity impact evaluations that ensure compliance with environmental regulations and standards (Molavi, 2019); (Argyriou, 2023). Table 7 groups the main environmental KPIs.

Table 7: Environmental Sustainability KPIs.

KPI	Definition	Reference
Total energy consumption	Energy consumption per TEU or per ton of cargo handled	Gu et al. (2023); Sadiq et al. (2021)
Renewable energy share	Percentage of total energy consumption from renewable sources	Gu et al. (2023); Argyriou and Tsoutsos (2023)
Energy efficiency improvement rate	Year-over-year percentage improvement in energy efficiency	Sadiq et al. (2021); Wang et al. (2023)
Shore power utilization	Percentage of vessels using onshore power supply while berthed	Gu et al. (2023); Sadiq et al. (2021)
Carbon dioxide emissions	CO2 emissions per TEU or per ton of cargo handled	Wang et al. (2023); Gu et al. (2023)
Greenhouse gas emission intensity	Total GHG emissions per unit of throughput	Sadiq et al. (2021); Wang et al. (2023)
Air pollution index	Air quality measurements around port area	Gu et al. (2023); Molavi et al. (2019)
Noise level monitoring	Decibel levels at port boundaries and community areas	Gu et al. (2023); Argyriou and Tsoutsos (2023)
Water consumption per unit throughput	Liters of water consumed per TEU or per ton of cargo	Gu et al. (2023); Molavi et al. (2019)
Waste generation rate	Tons of waste generated per unit of throughput	Argyriou and Tsoutsos (2023); Gu et al. (2023)
Waste recycling rate	Percentage of total waste that is recycled	Gu et al. (2023); Argyriou and Tsoutsos (2023)
Environmental impact assessment score	Comprehensive assessment of port's environmental performance	Makkawan et al. (2023); Molavi et al. (2019)

Source: Authors.

- Governance and Compliance KPIs.

Based on the literature review, several governance and compliance KPIs are identified as existing metrics in smart port evaluation frameworks as seen in table 8.

- Connectivity and Integration KPIs.

Several connectivity and integration KPIs are well-established in smart port evaluation frameworks according to table 9.

Table 8: Governance and Compliance KPIs.

KPI	Definition	Reference
Environmental regulation compliance	Adherence to environmental standards and regulations	Molavi et al. (2019); Gu et al. (2023)
International standard certification	Number of ISO and other international certifications maintained	Molavi et al. (2019); Argyriou and Tsoutsos (2023)
Risk management effectiveness	Number of risk incidents prevented or mitigated	Durlik et al. (2024); Paraskevas et al. (2025)

Source: Authors.

Table 9: Connectivity and Integration KPIs.

KPI	Definition	Reference
Intermodal connectivity	Quality of rail, road, and inland waterway connections	Makkawan et al. (2023); Ricardianto et al. (2022)
Digital connectivity	Data exchange capabilities with supply chain partners	Sahraoui et al. (2023); Zhou and Suh (2024)
Data sharing efficiency	Real-time data exchange capabilities	Sahraoui et al. (2023); Makkawan et al. (2023)

Source: Authors.

- Infrastructure and Capacity KPIs.

Infrastructure and capacity KPIs are fundamental metrics for evaluating smart port performance across multiple operational dimensions as explained table 10.

Table 10: Infrastructure and Capacity KPIs.

KPI	Definition	Reference
Terminal area utilization	Efficient use of available terminal space	Zhou and Suh (2024); Fri et al. (2020)
Berth length efficiency	Cargo handled per meter of berth length	Zhou and Suh (2024); Wang et al. (2023)
Crane productivity	Container moves per crane per hour	Zhou and Suh (2024); Sahraoui et al. (2023)
Storage capacity utilization	Percentage of storage capacity effectively used	Sahraoui et al. (2023); Zhou and Suh (2024)
Equipment utilization rate	Percentage of time equipment is productively used	Zhou and Suh (2024); Fri et al. (2020)
Infrastructure capital investment	Infrastructure investment as percentage of revenue	Gu et al. (2023)

Source: Authors.

3.3. RQ3.- Evaluation Models and Frameworks.

3.3.1. Performance Models.

Data Envelopment Analysis (DEA) Models: DEA models represent a prominent approach to port efficiency evaluation. Fri et al. (2020) utilized DEA with 12 inputs and 2 outputs to evaluate container terminal performance in Morocco. Nadarajan et al. (2023) employed triangular and trapezoidal fuzzy DEA models to handle uncertainty in seaport network efficiency measurement. Wang et al. (2023) applied DEA to assess carbon emission reduction potential in Yangtze River Delta ports.

Multi-Criteria Decision Analysis**:** Paraskevas et al. (2025) utilized Neutrosophic Cognitive Maps to support group decisions about smart port performance modeling. This approach addresses uncertainty and ambiguity in expert opinions while capturing dynamic interactions among performance indicators.

3.3.2. Indices Framework.

The development of comprehensive port performance measurement systems has become essential for evaluating modern maritime operations, with various specialized indices addressing different aspects of port functionality. These indices can be categorized into three main types: Smart Port, Green Port, and Hybrid indices, each addressing specific operational and environmental concerns.

Smart Port Index (SPIn): this index evaluates ports across four critical domains: Safety and Security, Operations, Environment, and Energy, utilizing multiple key performance indicators to provide a holistic assessment of smart port capabilities.

Green Port Indices are:

- Carbon Emission Reduction Potential Index: this environmental assessment index that measures ports on a 0-1 efficiency scale, focusing on environmental efficiency, CO_2 emissions, and energy consumption patterns.

- Port Sustainability Performance Index: this comprehensive sustainability index encompassing four key categories: environmental, social, economic, and operational performance indicators.

- Green Port Energy Efficiency Index: this specialized index incorporating eight key metrics including GHG emissions, energy consumption, carbon footprint, energy efficiency, operational performance, and grid stability.

Performance and Connectivity Indices are:

- Container Port Performance Index: this multi - dimensional assessment index covering productivity, cost, efficiency, and reputation across four distinct areas.

- Liner Shipping Connectivity Index (LSCI) : As analyzed by Nadarajan, Ahmed, and Noor (2023), this index evaluates port connectivity through five components: ships, vessel capacity, vessel size, services, and shipping companies.

- Logistics Effectiveness Index: this index addressing accessibility, cargo transport regulations, logistics effectiveness, and port operational performance across four main dimensions.

3.3.3. Environmental, Social, and Governance (ESG) Frameworks.

Gu et al. (2023) applied ESG frameworks to evaluate sustainable port development in China. This comprehensive approach integrates environmental, social, and governance indicators to assess holistic port sustainability performance.

3.3.4. Classic Evaluation Frameworks.

Fri et al. (2019) reviewed multiple evaluation models including Activity-Based Costing (ABC), ECOGRAI, and Balanced Scorecard (BSC). These models address different organizational types, decision levels, and performance indicator types, providing flexibility for various port contexts as seen in table 11.

Table 11: Classic port performance measurement models.

Model Name	Use Classification	Flow Type	Application Context	Performance Indicators
ABC (Activity-Based Costing)	Cost and Margin Analysis	Physical	Industrial	Cost, Margin
BSC (Balanced Scorecard)	Performance Measurement	Informational	Both (Industrial and Service)	Financial and Non-financial
PPMS (Performance and Process Management System)	Performance Monitoring	Informational	Industrial	Financial, Innovation, Customer, Employee
ECOGRAI	Performance Benchmarking	Informational	Academic	Internal and External Benchmarking
Functionality Economy (FE)	Sustainability and Efficiency	Physical and Financial	Academic	Sustainability Indicators
ASLOG Audit	Supply Chain Audit	Informational and Physical	Industrial	Tactical and Operational
SASC (Strategic Audit Supply Chain)	Strategic Audit	Informational and Physical	Academic	Strategic, Tactical, Operational
Model PPMS (2019)	Performance Measurement	Informational	Industrial	Financial, Innovation, Customer, Employee
GRAI (Generalized Resource Allocation and Intelligent)	Scheduling and Coordination	Informational	Academic	Operational and Strategic

Source: Authors.

3.4. RQ4.- Smart and green ports implementation Strategies.

Based on the literature review of smart ports, several key strategies emerge for developing and implementing smart port initiatives. These strategies can be organized into distinct but interconnected domains that collectively contribute to port transformation.

- Smart Port Operation Domain Strategies.

The operational domain focuses on infrastructure development and efficiency enhancement through advanced technologies. Strategic focus on infrastructure development and operational efficiency enhancement through implementing automation equipment for internal cargo movement such as Automated Guided Vehicles (AGV), Automated Stacking Cranes (ASC), Quay Cranes (QC), and robots (Makkawan et al., 2023). Additionally, using smart platforms for information exchange within the port community, including Blockchain and Cloud technologies and deploying technologies for port traffic and cargo tracking systems like IoT, RFID, real-time tracking systems are essential components. The development of terrestrial connectivity infrastructure to improve road and railway access to the port represents another critical operational strategy (Makkawan et al., 2023).

- Environmental and Energy Management Strategies.

Sustainability acceleration forms a cornerstone of smart port development. Strategies aimed at sustainability acceleration through implementing smart sensors for environment and pollution monitoring to control and reduce emissions and promoting the use of clean and sustainable energy sources in port operations, including renewable electricity production like solar and wind power (Makkawan et al., 2023). The transition to greener technologies is further supported by energy-saving and emission reduction technologies, port oil-to-gas, oil-to-electricity, and ship-shore power supply, and technologies for energy structure optimization (Wang et al., 2023).

- Safety and Security Enhancement Strategies.

Security and safety improvements utilize cutting-edge technologies for comprehensive protection. Upgrading safety and security systems with advanced technologies such as AI, AR, VR, and Digital Twin for safety training and simulations, using RFID and intelligent CCTV systems for safety monitoring, and implementing AI-based intelligent biometric access control and automatic license plate recognition for enhanced security and access automation (Makkawan et al., 2023). Investment in cybersecurity measures and infrastructure protection from digital threats represents an increasingly critical component of this domain.

- Technological Integration and Digital Transformation Strategies.

The integration of advanced technologies forms the backbone of smart port development. Utilization of Information Technology Systems: Introducing digital systems for ship loading and unloading activities to increase efficiency and stakeholder coordination (Ricardianto et al., 2022). Furthermore, implementation of smart port technologies through gradual technological adoption, policy and investment support, standardization and framework development, capacity building and workforce training, pilot programs and phased rollouts, integration of digital ecosystems, and monitoring and continuous improvement (Zhou and Suh, 2024).

- Governance and Policy Strategies.

Effective governance models are essential for successful smart port implementation. Landlord Port Model: Characterized by port authorities acting as landlords who own the port infrastructure and lease it to operators, encouraging market-oriented management and private sector participation, Public-Private Partnership (PPP) Model: A collaborative framework where public authorities and private companies jointly invest and manage port operations (Gu et al., 2023). Policy support includes implementing policies that support sustainable port operations, including regulation of operational hours and infrastructure development aligned with environmental and local conditions (Ricardianto et al., 2022).

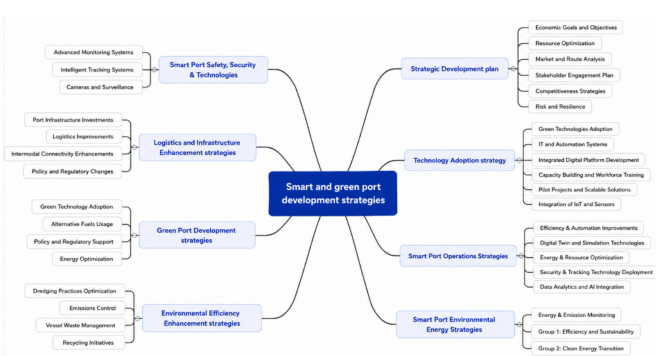
- Stakeholder Engagement and Communication Strategies.

Successful smart port development requires comprehensive stakeholder involvement. The strategy development process includes examining goals and objectives, conducting gap analysis, involving stakeholders through interviews, surveys, workshops, and community consultations, identifying and prioritizing strategies, developing implementation plans, communicating the strategies, and monitoring and evaluating (Argyriou and Tsoutsos, 2023). This approach ensures that diverse perspectives are considered and that strategies are effectively communicated and implemented.

- Infrastructure and Capacity Development Strategies.

Physical and digital infrastructure development remains fundamental to smart port success. Enhancement of road infrastructure and traffic engineering: Improving roads leading to and within the port to facilitate smoother cargo movement and reduce congestion and development of alternative transportation routes: Creating multiple access roads and optimizing traffic flow to improve accessibility and operational performance (Ricardianto et al., 2022). Additionally, green port information infrastructure and low-carbon management and innovation strategies support the technological foundation required for smart port operations (Wang et al., 2023).

Figure 3: Smart and green port development strategies.



Source: Authors.

- Governance strategies.

Contemporary port authorities have adopted diverse governance models to navigate evolving global economic conditions and technological advancements. These frameworks reflect varying degrees of public and private sector involvement, each offering distinct advantages for port management and development (Gu et al., 2023). The principal models include:

Landlord Port Model: Characterized by port authorities acting as landlords who own the port infrastructure and lease it to operators. This model encourages market-oriented management and private sector participation.

Concession Model: Involves granting concessions to private companies to operate port facilities, leading to a more privatized and entrepreneurial management approach.

Public-Private Partnership (PPP) Model: A collaborative framework where public authorities and private companies jointly invest and manage port operations. This model aims to combine public oversight with private sector efficiency.

Full Private Ownership: Exemplified by ports in some regions such as the UK, where ports are entirely owned and operated by private entities without direct government involvement.

- Key Success Factors.

The successful implementation of port performance measurement systems and smart port initiatives requires careful consideration of several critical success factors, that form the foundation of effective strategic deployment, which are:

Stakeholder Engagement emerges as a fundamental requirement, emphasizing the necessity for multi-stakeholder collaboration and alignment across all port ecosystem participants, as highlighted by Argyriou and Tsoutsos (2023) and Paraskevas et al. (2025).

Phased Implementation represents another crucial strategy, advocating for gradual adoption approaches that minimize operational risks while enabling organizational learning and adaptation, as demonstrated in studies by Zhou and Suh (2024) and Sahraoui et al. (2023).

Policy Support serves as an essential enabler, requiring robust government backing and comprehensive regulatory frameworks to provide the necessary institutional foundation, as emphasized by Zhou and Suh (2024) and Gu et al. (2023).

Technology Integration demands the development of comprehensive digital ecosystem architectures that seamlessly connect various port operations and stakeholders, as identified by Zhou and Suh (2024) and Makkawan et al. (2023).

Capacity Building focuses on workforce training and skill development initiatives to ensure human capital readiness for advanced port operations, as noted by Zhou and Suh (2024) and Sahraoui et al. (2023).

Continuous Monitoring establishes the framework for ongoing performance evaluation and strategic adjustment, enabling ports to adapt and optimize their operations continuously, as recommended by Argyriou and Tsoutsos (2023) and Zhou and Suh (2024).

3.5. RQ5.- Opportunities and Challenges.

- Smart and green Port Development Opportunities.

Numerous opportunities emerge for port transformation and development. They span technological, operational, environmental, and economic domains, offering significant potential for enhancing port performance and competitiveness.

- Advanced Technology Integration Opportunities.

Machine Learning and Artificial Intelligence Applications: AI can enhance prediction and decision-making capabilities, leading to optimized maritime operations through methods like deep learning and reinforcement learning (Durlik et al., 2024). AI-driven solutions help in route optimization, ensuring vessels take the most efficient paths, and smart energy management systems enhance overall operational efficiency on board. AI plays a significant role in autonomous shipping by enabling navigation systems to operate with increased autonomy and improves logistics management for shipping operations (Durlik et al., 2024).

Internet of Things (IoT) Integration: the integration of Internet of Things (IoT) technologies allows for the development of sophisticated and interconnected systems that can provide real-time data from ships, ports, and cargo containers, enabling better operational efficiency and maintenance (Durlik et al., 2024). IoT devices for real-time monitoring and control of logistics operations, equipment status, energy consumption, and fuel utilization support predictive maintenance, improve operational efficiency, and reduce downtime (Muhammad Sadiq et al., 2021).

Edge Computing and Connectivity Solutions: Implementing edge computing can address connectivity issues by allowing local data processing, resulting in reduced latency and enhanced reliability for AI applications in remote maritime environments (Durlik et al., 2024). This technology enables more responsive and efficient port operations by processing data closer to the source.

- Operational Opportunities.

Automation and Efficiency Enhancement: Implementation of automation equipment for internal cargo movement such as Automated Guided Vehicles (AGV), Automated Stacking Cranes (ASC), Quay Cranes (QC), and robots offers significant opportunities for operational improvement (Makkawan et al., 2023). Automation technologies enhance port operations by increasing efficiency and safety, including automated cranes, robotic vehicles, and self-operating machinery, which support efficient handling of cargo and maintenance tasks (Argyriou and Tsoutsos, 2023).

Predictive Maintenance and Asset Management: AI algorithms can predict equipment failures and maintenance needs by analyzing data from sensors and historical performance, thereby reducing downtime and maintenance costs (Durlik et al., 2024). Usage of machine learning-based asset predictors to monitor equipment health and optimize maintenance schedules helps reduce failures and improve operational uptime (Muhammad Sadiq et al., 2021).

Real-time Operations Management: Real-time cargo tracking and management systems and deployment of technologies for port traffic and cargo tracking systems like IoT, RFID, real-time tracking systems provide opportunities for enhanced operational visibility and control (Makkawan et al., 2023). IoT plays a crucial role in enabling real-time data collection, asset monitoring, and improved logistical management (Argyriou and Tsoutsos, 2023).

- Environmental and Sustainability Opportunities.

Green Technology Development: AI technologies can drive the implementation of sustainable practices, such as the use of alternative fuels (e.g., hydrogen and ammonia), contributing to reduced environmental impact and promoting circular economy initiatives (Durlik et al., 2024). Shore Power Technology enables ships to connect to onshore electricity supplies, reducing emissions from ships operating while docked, requiring infrastructural transformation and cooperation across sectors for effective implementation (Gu et al., 2023).

Energy Efficiency and Renewable Integration: Energy - saving technologies and smart energy management systems, sustainable resource utilization strategies, and commitment to environmental regulations and international standards offer significant opportunities for ports to reduce their environmental footprint (Makkawan et al., 2023). Adoption of renewable energy sources such as wind and solar power, as well as alternative fuels for ships and port vehicles, aims to reduce emissions and environmental impact (Argyriou and Tsoutsos, 2023).

Emission Reduction and Environmental Monitoring: AI systems are employed for real-time monitoring of air and water quality, allowing for better compliance with environmental regulations and enhancing overall sustainability efforts (Durlik et al., 2024). Application of smart pollution sensors for monitoring and reducing emissions from port activities and environmental impact assessment and control systems provide opportunities for continuous environmental improvement (Makkawan et al., 2023).

- Economic and Financial Opportunities.

Cost Reduction and ROI Enhancement: the potential for improved fuel efficiency, reduced maintenance costs, and optimized operations provides compelling financial incentives for companies to adopt AI technology (Durlik et al., 2024). Cost savings, trade growth opportunities, and lower emissions compliance provide economic benefits while addressing environmental concerns (Sahraoui et al., 2023).

Revenue Generation and Market Expansion: Faster turnaround times, fewer operational errors, and improved service quality can lead to increased throughput and enhanced competitiveness in global markets (Sahraoui et al., 2023). Enhanced port operations can attract more shipping lines and cargo, directly impacting revenue generation capabilities.

- Digital Transformation Opportunities.

Platform Integration and Data Analytics: using smart platforms for information exchange within the port community, including Blockchain and Cloud technologies, and Big Data analytics for forecasting and operational planning offer opportunities for enhanced decision-making and coordination (Makkawan et al., 2023). Use of big data and cloud platforms to handle large volumes of operational data, optimize resource utilization, and support decision-making processes related to energy management and sustainability (Muhammad Sadiq et al., 2021).

Blockchain and Security Enhancement: blockchain Technology is utilized for enhancing transparency, security, and efficiency in transactions and processes related to port operations

(Paraskevas et al., 2025). Implementation of smart platforms for exchanging information within the port community using Blockchain technology provides opportunities for secure and transparent operations.

- Collaborative and Partnership Opportunities.

Industry Collaboration and Government Support: Building partnerships between industry players and government support can accelerate AI development and implementation, helping to overcome financial and regulatory barriers (Durlik et al., 2024). Public-Private Partnership (PPP) Model provides a collaborative framework where public authorities and private companies jointly invest and manage port operations, combining public oversight with private sector efficiency (Gu et al., 2023).

Knowledge Transfer and Capacity Building: Replicable solutions in other ports offer opportunities for knowledge transfer and scaling of successful smart port initiatives (Sahraoui et al., 2023). Implementation of e-administration and digital platforms, such as e-permitting and online stakeholder engagement platforms, facilitate effective communication and decision - making (Argyriou and Tsoutsos, 2023).

- Market Competitiveness Opportunities.

Service Quality Enhancement: Digital and Communication Technologies (DCTs) such as interactive websites, social media marketing, and digital communication tools improve port competitiveness and strategic decision-making (Zhou and Suh, 2024). Enhanced customer satisfaction through improved service reliability and operational efficiency creates competitive advantages in the maritime industry.

Global Connectivity and Integration: Enhanced integration into global shipping networks through improved Liner Shipping Connectivity Index (LSCI) performance, which measures how well a country's ports are integrated into global shipping networks (Nadarajan et al., 2023). This integration opens opportunities for increased trade volumes and enhanced global market access.

- Smart and Green Port Development Challenges and Barriers.

Based on the comprehensive literature review of smart ports, numerous challenges and barriers impede the successful implementation and development of smart port initiatives. These barriers span technological, financial, organizational, regulatory, and operational domains, creating complex obstacles that require strategic solutions.

- Financial and Economic Barriers.

High Implementation Costs: the initial investment required for AI infrastructure, including hardware, software, and skilled personnel, is often prohibitively high, posing a significant deterrent, particularly for small- to mid-sized enterprises (Durlik et al., 2024). High capital costs and investment risks represent major barriers to implementing green technologies and smart port solutions (Muhammad Sadiq et al., 2021). High upfront investment requirements create significant financial challenges for ports seeking to modernize their operations (Sahraoui et al., 2023).

Return on Investment Uncertainty: the uncertainty surrounding the return on investment for smart port technologies creates hesitation among port operators and investors. The long payback periods associated with major infrastructure investments in smart technologies compound these financial concerns, making it difficult to justify expenditures in competitive market environments.

- Technological and Infrastructure Barriers.

Legacy Systems Integration: many maritime operations depend on outdated systems that are incompatible with modern AI technologies, making integration difficult and costly (Durlik et al., 2024). Infrastructure complexity and integration challenges pose significant obstacles to implementing comprehensive smart port solutions (Muhammad Sadiq et al., 2021). Legacy systems limit green technology adoption and create compatibility issues with new smart port technologies (Sahraoui et al., 2023).

Data Quality and Management Issues: AI systems require high-quality data for effective training and operation. Fragmented and inconsistent data due to the nature of maritime operations can significantly hinder AI performance (Durlik et al., 2024). Data management and interoperability issues create barriers to seamless integration of smart port technologies (Muhammad Sadiq et al., 2021). Combining qualitative and quantitative data from various stakeholders and ensuring that these data can be effectively integrated into a cohesive framework remains a complex issue (Paraskevas et al., 2025).

Connectivity and Communication Limitations: Limited connectivity in remote maritime environments affects real-time data transmission and can hinder the functionality of AI systems, making it challenging to implement AI solutions effectively (Durlik et al., 2024). Energy supply security and grid stability issues create additional technological barriers to smart port implementation (Muhammad Sadiq et al., 2021).

- Organizational and Human Resource Barriers.

Shortage of Skilled Personnel: it exists a significant lack of professionals with expertise in AI, data science, and machine learning within the maritime sector, which limits effective AI deployment and operation (Durlik et al., 2024). Training gaps and the need for capacity building present ongoing challenges for smart port implementation (Sahraoui et al., 2023). The shortage of qualified personnel capable of operating and maintaining advanced smart port technologies creates bottlenecks in implementation efforts.

Resistance to Change: Cultural resistance within established maritime companies can impede the acceptance of new technologies, requiring substantial change management efforts to overcome (Durlik et al., 2024). Stevedore resistance and organizational inertia create barriers to adopting new technologies and operational procedures (Sahraoui et al., 2023). Resistance to change from traditional port operators and workers represents a significant organizational barrier to smart port development.

- Regulatory and Compliance Barriers.

Complex Regulatory Environment: Navigating the complex web of national and international regulations can be resource-intensive and challenging, slowing down AI adoption efforts (Durlik et al., 2024). Lack of unified global criteria for port decarbonization and limited implementation of regulatory policies create regulatory uncertainty (Muhammad Sadiq et al., 2021). Environmental and regulatory diversity across different jurisdictions complicates standardized implementation of smart port solutions.

Compliance and Standards Challenges: the handling of vast amounts of sensitive operational and proprietary data raises crucial concerns about data privacy and the risk of cyberattacks, complicating compliance with data protection regulations (Durlik et al., 2024). Cybersecurity and job displacement risks create additional compliance and social responsibility challenges (Sahraoui et al, 2023).

- Operational and Performance Barriers.

Managing Uncertainty and Complexity: one of the significant challenges in evaluating smart port performance is handling the uncertainties and ambiguities associated with expert opinions, which can lead to inconsistent judgments (Paraskevas et al., 2025). Capturing the evolving and dynamic interactions among the various performance indicators presents difficulties in maintaining accurate assessments over time (Paraskevas et al., 2025).

Stakeholder Coordination Challenges: achieving consensus among diverse stakeholders with potentially conflicting interests can complicate the decision-making process (Paraskevas et al., 2025). External factors such as political instability, economic crises, and global events like the COVID-19 pandemic can hinder full adoption of smart port technologies (Sahraoui et al., 2023).

Operational Constraints: Operational constraints and equipment limitations create practical barriers to implementing smart port solutions effectively (Muhammad Sadiq et al., 2021). Container dwell time issues, such as long container stay durations (18 days vs. 6-7 days in more efficient ports), demonstrate operational inefficiencies that must be addressed (Sahraoui et al., 2023).

- Environmental and Sustainability Barriers.

Sustainability Integration Challenges: sustainability concerns may hinder innovation in some cases, and some models lack consideration of KPI interactions, creating barriers to comprehensive sustainability implementation (Fri et al., 2019). Balancing economic, social, and environmental priorities presents ongoing challenges for sustainable port development (Gu et al., 2023).

Environmental Compliance Complexity: Environmental impact assessment and control systems require sophisticated monitoring and compliance mechanisms that can be challenging to implement and maintain (Makkawan et al., 2023). The complexity of environmental regulations and the need for continuous monitoring create ongoing operational challenges.

- Technology Adaptation and Integration Barriers.

Technological Adaptation Challenges: keeping up with rapid technological advancements and integrating them into existing port infrastructures is a continual challenge for smart ports (Paraskevas et al., 2025). The rapid pace of technological change requires continuous investment in updates and training, creating ongoing resource demands.

System Integration Complexity: the integration of multiple smart port technologies into cohesive systems presents technical challenges related to interoperability, data sharing, and system coordination. The complexity of creating seamless integration between different technological components can create implementation delays and cost overruns.

- Market and Competitive Barriers.

Market Uncertainty: uncertainty about market demand for smart port services and the competitive landscape can create hesitation in investment decisions. The need to maintain competitiveness while investing in unproven technologies creates a challenging balance for port operators.

Competitive Pressure: the pressure to maintain current operations while implementing new technologies creates operational challenges. Ports must balance the need for continuous service delivery with the disruption associated with technological upgrades and system implementations.

- Security and Risk Management Barriers.

Cybersecurity Concerns: Data privacy and security concerns related to the handling of vast amounts of sensitive operational and proprietary data raise crucial concerns about cyberattacks and data breaches (Durlik et al., 2024). The increasing reliance on digital systems creates vulnerability to cyber threats that require sophisticated security measures.

Risk Assessment Complexities: the complexity of assessing and managing risks associated with new technologies, particularly in mission-critical port operations, creates barriers to adoption. The need for comprehensive risk management frameworks adds complexity and cost to smart port implementation efforts.

Conclusions.

Key finding.

This systematic review provides comprehensive insights into smart port development, revealing the complex interplay between technology, performance measurement, and implementation strategies. The analysis of 18 studies demonstrates that successful smart port initiatives require integrated approaches combining technological innovation with environmental responsibility, stakeholder engagement, and strategic planning.

The study identifies IoT, AI, automation, 5G, and renewable energy systems as foundational technologies for smart and green ports. These enable real-time monitoring, predictive maintenance, and emission reductions. While these technologies enhance efficiency, their adoption faces barriers such as high costs and legacy system integration. Ports must prioritize scalable, interoperable solutions to ensure long-term viability. Future research should explore cost-effective deployment models, particularly for smaller ports.

Current KPIs and SPIs are fragmented, with gaps in standardized metrics for sustainability and digitalization. The study proposes a multi-dimensional framework covering operational, environmental, financial, and social indicators. Standardization is crucial for benchmarking and policy-making. However, regional variations in port operations (e.g., cargo types, infrastructure) may require adaptable metrics. Effective smart port implementation relies on public-private partnerships (PPPs), policy incentives, and multi-stakeholder engagement (e.g., port authorities, shipping lines, tech providers). While PPPs mitigate financial risks, conflicting stakeholder priorities (e.g., profit vs. sustainability) can hinder progress. Policymakers must balance regulation with innovation incentives.

Green technologies (e.g., shore power, LNG, waste recycling) reduce emissions but require integration with digital systems (e.g., AI for energy optimization). Ports often treat ”smart” and ”green” initiatives separately, missing synergies. Future strategies should adopt circular economy principles, linking digital tools to track carbon footprints and resource use. Key challenges include high costs, cybersecurity risks, and workforce skill gaps. Opportunities lie in AI-driven predictive analytics, automation, and renewable energy microgrids. Addressing these challenges demands targeted investments and training programs. For example, ports could pilot AI-powered energy grids to demonstrate ROI before scaling. Future studies should assess the socio-economic impact of automation on port labor.

Limitations and Future Outcomes.

This study has several limitations that should be acknowledged. First, its temporal scope (2019-2025) and English - language restriction may have excluded earlier foundational works and relevant non-English publications. Second, reliance solely on Scopus and Web of Science databases potentially omitted valuable studies from other sources. Third, the academic focus might underrepresent practical industry perspectives from port authorities and operators. Fourth, the rapid evolution of technologies like AI and blockchain means some cutting-edge innovations may not yet be reflected in peer-reviewed literature. Fifth, while the PRISMA methodology ensured rigor, it may have excluded valuable qualitative insights. Finally, findings may not generalize across all port types due to operational scale differences. Building on this study's findings and limitations, several critical directions emerge for future research and practical implementation:

Technological Integration and Innovation: Future works can explore next - generation technologies like quantum computing for logistics optimization, advanced digital twins for real-time port simulations, and hydrogen fuel cell applications for zero-emission operations. The integration of generative AI for predictive maintenance and autonomous decision-making in port operations presents another promising avenue. Research should particularly focus on cost-effective technology deployment strategies suitable for ports in developing regions.

Standardization and Performance Metrics: There is urgent need to develop globally accepted, yet adaptable, performance measurement frameworks that can accommodate regional variations while enabling meaningful benchmarking. Future work should validate the proposed KPI/SPI frameworks through large-scale empirical studies across diverse port ecosystems, with special attention to developing standardized metrics for social impact and resilience.

Policy and Governance Models: Research should investigate innovative governance structures that balance public oversight with private sector efficiency, particularly for emerging economies. This includes studying the effectiveness of carbon credit systems for ports, the impact of IMO 2030/2050 regulations, and the development of ”sandbox” approaches for testing new technologies under regulatory supervision.

Sustainability and Circular Economy: Future perspectives must emphasize closed-loop systems in ports, including waste-to-energy conversion, seawater desalination powered by renewable energy, and circular supply chain models. Lifecycle assessments of green port technologies and studies on biodiversity-positive port designs will be crucial for true sustainability.

Human Capital: As automation increases, research must address workforce reskilling strategies and the social implications of port digitalization. This includes developing training frameworks for emerging port technologies and studying models for equitable technology adoption across global ports.

Resilience and Climate Adaptation: Future studies should focus on climate-resilient port designs, including flood mitigation systems, renewable energy microgrids, and adaptive infrastructure for rising sea levels. Research on ports as hubs for offshore wind energy and blue economy initiatives presents another promising direction. In this section we present the conclusions, at least one for each objective stated in the introduction.

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