Smart Ecoport 5.0: Criteria, Implementation, and Challenges in Sustainable Port Management

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Abstract.
Modern ports face dual pressures to enhance operational efficiency and environmental sustainability while ensuring resilience against disasters and climate change. The "Smart Ecoport 5.0" concept emerges as a new holistic paradigm, integrating advanced digital technologies, ecological principles, and disaster resilience strategies. This research aims to identify and analyze the key criteria that constitute Smart Ecoport 5.0 through a systematic literature review of scientific publications from the last 10 years, analysis of international regulations, and comparative case studies of advanced and developing ports. The research findings outline essential criteria encompassing smart port design and modeling, clean energy adoption, supply chain digitalization, and vessel operational automation, as well as the integration of sustainable multimodal transport and adaptive port governance. The main novelty of the Smart Ecoport 5.0 concept lies in its synergistic emphasis on technology-driven efficiency and a strong commitment to sustainability, supported by adaptive capacity and resilience to environmental and operational risks. This concept transcends traditional smart port concepts by explicitly integrating green infrastructure and disaster resilience pillars as core components, rather than mere additions. The implementation of this concept will significantly improve port performance globally, reduce the maritime carbon footprint, and ensure operational continuity amidst uncertainty.
Keywords: Smart Ecoport 5.0, Sustainable Port, Green Infrastructure, Disaster Resilience, Port Digitalization, Maritime Transport

1. Introduction

Modern ports are vital nodes within the global logistics network, serving as crucial convergence points for economic activity, infrastructure, and the environment (Merk, 2014; Rodrigue, 2018). Amid rising trade volumes and complex global challenges, including climate change, supply chain disruptions, and the risk of natural or operational disasters, there is a growing urgency to enhance operational efficiency, promote environmental sustainability, and strengthen the resilience of port infrastructure. Responding to this complexity has led to the evolution of the port concept, from "green ports" focused on reducing environmental impact to "smart ports" emphasizing efficiency through digitalization and automation. However, these approaches are often fragmented or have not fully integrated the aspect of resilience.

To meet these demands, the "Smart Ecoport 5.0" concept emerges as a comprehensive paradigm that integrates advanced digital technology, sustainable ecological principles, and disaster mitigation and adaptation strategies (Heikkilä et al., 2022). This concept aims to create ports that achieve optimal operational efficiency, prioritize environmental responsibility, and demonstrate robustness and adaptability in the face of diverse risk and unforeseen disruptions. The emphasis on the "Eco" pillar includes the adoption of clean energy, effective waste management, and the integration of green infrastructure such as cold ironing (Pavlic et al., 2014; Prousalidis &

D'Agostino, 2023). Meanwhile, the "Smart" dimension focuses on operational digitalization, process automation, and the utilization of big data and artificial intelligence for supply chain optimization and real-time decision-making (Min, 2022; Yau et al., 2020). The fundamentally integrated "Resilient" aspect ensures the port's ability to anticipate, absorb, and recover from external shocks, whether due to climate change (e.g., sea-level rise, extreme weather) or operational incidents (Asariotis et al., 2024; Henud et al., 2024)

The global impetus for transitioning towards more sustainable and resilient ports has been initiated by various international regulations and policies. Organizations such as the International Maritime Organization (IMO) have issued strategies to reduce greenhouse gas emissions from ships (IMO, 2018), while standards like ISO 14001 and global climate agreements such as the Paris Agreement promote sustainable practices across the maritime sector. Furthermore, bodies like the United Nations Economic Commission for Europe (UNECE) actively promote sustainable transport and logistics (WBG, 2020). However, in practice, the implementation of the holistic Smart Ecoport 5.0 concept faces significant challenges. These obstacles include varying digital and physical infrastructure readiness among countries, limited adaptive local regulations, and high initial investment costs for smart technologies and green infrastructure (Othman et al., 2022; Rahayu et al., 2024). Integrating these diverse technologies and principles requires a comprehensive multidisciplinary approach.

Given this complexity and urgency, in-depth research is needed to clearly define the essential criteria that constitute a Smart Ecoport 5.0. This research aims to (1) identify and analyze the holistic criteria of Smart Ecoport 5.0 through a comprehensive systematic literature review, (2) compare the implementation of this concept across both developed and developing countries by examining selected case studies to understand key differences and best practices, and (3) provide strategic recommendations based on global best practices and international regulations to support the development and benchmarking of sustainable ports within the context of Smart Ecoport 5.0. Thus, this research contributes to the establishment of a more refined framework for the transformation of global ports towards a more efficient, sustainable, and resilient future.

2. Research Method

2.1. Systematic Literature Review

A systematic literature review was conducted to identify and synthesize relevant findings from scientific publications over the past 10 years (2015–2025). The primary scientific databases used include Scopus, project reports, and applicable national and international standards, using a combination of keywords such as 'smart port,' 'eco-port,' 'green port,' 'resilient port,' 'port digitalization,' 'sustainable maritime transport,' and 'port disaster resilience.'

The article selection process involves several stages:

1. Initial Search: Identify articles based on relevant keywords
2. Screening: Review titles and abstracts for relevance to the concepts of smart ecoport, sustainability, and port disaster resilience.
3. Eligibility: Read the full text of selected articles to ensure they are relevant to the research objectives.
4. Data Synthesis: Extraction of key data from eligible articles, including definitions, criteria, implementation, challenges, and performance metrics related to smart, green, and resilient ports. The results of this synthesis form the basis for the development of the Smart Ecoport 5.0 criteria.

2.2. Analysis of International/National Regulations and Policies

Document analysis was conducted on regulations, standards, and policies issued by international organizations (e.g., International Maritime Organization - IMO, United Nations Economic Commission for Europe - UNECE, International Transport Forum - ITF) as well as relevant national policies on sustainable port development, energy efficiency, and disaster resilience. The aim is to understand the normative framework and incentives that drive the transition towards Smart Ecoport 5.0.

2.3. Comparative Case Studies

To gain an empirical understanding of the implementation of Smart Ecoport 5.0, this study involves a comparative case study of leading ports in various parts of the world. The selection of case studies is based on their level of progress in implementing smart, eco, and resilient port elements, including ports in developed countries (e.g., Rotterdam, Singapore, Hamburg, Los Angeles) and several in developing countries (e.g., Shanghai, Busan). This analysis focuses on:

1) Implementation of digitalization and automation initiatives.
2) Application of clean energy technologies and green infrastructure.
3) Risk management and disaster resilience strategies.
4) Multimodal transport integration.
5) Governance structures and stakeholder collaboration.

2.4 Benchmarking Approach

Based on data collected from literature reviews and case studies, benchmarking was conducted to identify best practices and key performance indicators (KPIs) relevant to Smart Ecoport 5.0. The results of this benchmarking were used to formulate practical and targeted recommendations for the development of future ports. This approach enables a systematic comparison between theoretical criteria and practical implementation, resulting in a solid and applicable framework.

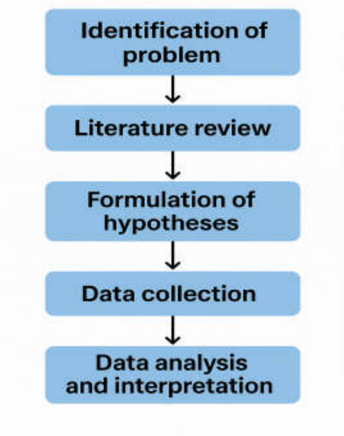


Figure 1. Smart Ecoport 5.0 Research Flowchart: Criteria, Implementation, and Challenges in Sustainable Port Management

3. Study of Smart Ecoport 5.0 Criteria

This study focuses on the key criteria that Smart Ecoport 5.0 must have to function optimally as a smart, environmentally friendly port based on sustainable green infrastructure and disaster resilience. Each criterion is analyzed based on a scientific approach, regulations, actual implementation in global ports, and case studies that support best practices in the maritime industry.

3.1. Smart Port Design and Modeling

The smart port concept represents a paradigm shift in maritime logistics, integrating advanced technology and sustainable practices to enhance the efficiency, safety, and environmental performance of port operations (Al-Fatlawi & Motlak, 2023; Min, 2022). This transformation is driven by the need to manage increasing cargo volumes and meet sustainability targets (International Transport Forum, 2024). Central to this evolution is the implementation of automation and digitalization, enhanced connectivity to optimize logistics, and energy management (Min, 2022; Yau et al., 2020).

Automation and digitalization play a vital role by utilizing Industry 4.0 solutions to reduce human intervention and improve asset utilization (Al-Fatlawi & Motlak, 2023). This includes the use of digital twins, artificial intelligence (AI), and blockchain to enhance logistics visibility and security (Alahmadi et al., 2021; González-Cancelas, Vaca-Cabrero, et al., 2025). Smart container management systems further optimize resource use while bolstering the safety of both assets and cargo (Belmoukari et al., 2023).

Advanced communication and connectivity serve as essential foundations for smart port design. The adoption of 5G networks facilitates real-time data transmission and enables applications like Virtual Reality (VR) for staff training and smart decision-making (Bartsiokas et al., 2025; Han et al., 2022). Furthermore, reliable vehicular communication networks support autonomous vehicles (AGVs and UAVs), ensuring efficient data exchange and rapid decision-making for container handling and other operational tasks (Almansor et al., 2025; Han et al., 2022).

To achieve sustainable energy management, smart ports prioritize electrification and the incorporation of renewable energy sources including marine-based renewables to lower their environmental impact and advance energy self-sufficiency (Clemente et al., 2023; Prousalidis & D'Agostino, 2023; Suárez, 2020). The implementation of smart grids and microgrids ensures efficient energy distribution. One notable feature is cold ironing, which enables ships to draw power from the port's electrical grid, thereby reducing local air pollution by eliminating reliance on diesel generators while docked (Elsisi et al., 2025; Pavlic et al., 2014).

To guide this development, performance metrics and indicators are essential. Smart Port Indicators (SPIs) are used to assess progress in operational efficiency, environmental sustainability, and safety (Makkawan & Muangpan, 2023), while Key Performance Indicators (KPIs) measure efficiency, sustainability, and innovation (W. Li et al., 2021). Finally, the intricate nature of smart port operations necessitates collaborative and strategic management, requiring distributed decision-making and control supported by advanced management functions and collaborative frameworks (Heikkilä et al., 2022).

3.2. Shipping and Maritime Industry

The smart port paradigm extends its transformative effects to the broader shipping and maritime industries, focusing on three key areas: clean energy adoption, supply chain digitalization, and the automation of ship operations, with the transition to clean energy as a primary focus. While fully electric ships face hurdles related to battery capacity and range, coordinated planning models for offshore charging stations are being explored to reduce costs (H. Li et al., 2023). Onboard solar photovoltaic systems are also proving effective at reducing greenhouse gas (GHG) emissions and air pollution on ships (Karatuğ & Durmuşoğlu, 2020). Alternative fuels like ammonia and advanced hybrid systems (e.g., SOFC-GT-ORC) are being developed to offer higher energy efficiency and lower emissions (Kim & Kim, 2023). The integration of renewable energy on offshore platforms further contributes to emission reductions and enhances sustainability (Micallef et al., 2025).

Supply chain digitalization is another critical area, as it improves operational efficiency, lowers costs, and strengthens security across maritime logistics (Seo et al., 2023). A case study from the Port of Rotterdam, for instance, highlights significant improvements achieved through the digitalization of port call operations (Suvadarshini & Dandapat, 2023). The integration of Supply Chain Management (SCM) systems, IoT-based tracking, and big data analytics boosts efficiency, transparency, and responsiveness(Fang et al., 2021). Additionally, blockchain-based platforms like TradeLens offer real-time access to shipping data, which improves visibility and reduces operational costs (Alahmadi et al., 2021). Despite these benefits, the transition faces several challenges, including high upfront investment costs, data security risks, and resistance to change (Kaštelan et al., 2024).

Finally, the automation of ship operations is transforming the face of maritime transport. Automatic navigation systems, such as AIS and GPS, significantly improve safety and efficiency by providing precise positional data and enabling data exchange between vessels (Menges et al., 2024). Within port environments, automated cranes and robotics systems optimize cargo handling processes, thereby reducing waiting times and operational costs (Belmoukari et al., 2023). This shift toward autonomous technology is redefining the role of crew members, who are increasingly focused on system monitoring, ultimately leading to greater efficiency, enhanced safety, and lower operational expenses (de Vos et al., 2021).

3.3. Multimodal Transportation and Port Management

These criteria emphasize efficient and sustainable transport integration, as well as an adaptive governance framework.

- Connectivity and Efficiency of Sustainable Transport Access: The level of connectivity between ports and major modes of transport (road, rail, barge) has a direct impact on the efficiency of goods distribution (Arvis et al., 2018; G. Wang et al., 2023). Ports in Northern Europe, such as Rotterdam and Hamburg, demonstrate high intermodal connectivity (Merk & Notteboom, 2015). The availability of low-emission transport modes, such as electric vehicles and bicycles, supports sustainability (Musolino et al., 2019). Infrastructure innovations like logistics tunnels can drastically reduce port access travel times. The adoption of environmentally friendly vehicles, such as electric buses, also serves as an essential indicator of sustainable transport access.
- Sustainable Multimodal Transport Integration: The integration of this transport systems represents a key pillar of the Smart Ecoport 5.0 framework (Tovar & Wall, 2022). At the Port of Shanghai, the implementation of inter-terminal transshipment platforms has effectively lowered the proportion of empty container movements and reduced diesel fuel consumption (N. Wang et al., 2019; Zhou et al., 2020) digitalization through the Port Community System (PCS) accelerates logistics processes, as demonstrated at the Port of Cotonou with a significant reduction in truck waiting times (Kirstein, 2018). Additionally, the development of green logistics corridors shows excellent potential for emissions reduction (Bullock et al., 2023).
- Port Transport Governance: Good governance emphasizes integrated strategic planning, inter-agency coordination, digitalization of logistics processes, low-emission regulations, and data transparency (Mdanat et al., 2024; Zeng et al., 2025). The Port Transportation Master Plan is a critical indicator of strategic integration (Ferrari et al., 2015). Inter-agency coordination forums such as IPCSA enhance the harmonization of cross-border

information systems. The digitalization of logistics through IoT improves throughput, although challenges related to data consistency persist (Prabowo et al., 2021). Moreover, data openness and shore power implementation have proven to reduce emissions and improve efficiency (Pavlinović et al., 2023)

- Internal Port Transportation Operations: Optimizing internal operations focuses on the application of smart technology and real-time data. Traffic density indices and overbooking reservation mechanisms (ORM) help minimize truck waiting times and increase terminal productivity (AlRukaibi et al., 2020; Wasesa et al., 2021). Traffic management systems (MASS Traffic Organisation Service) and digital transformation by major logistics companies contribute to improved movement efficiency and reduced congestion (Dagar et al., 2024; Guo et al., 2022). AI-based adaptive navigation technology and computer vision optimize the movement of container trucks in port areas (Chen et al., 2025; Zhu et al., 2025). Advanced sensors, such as the Marine Eye system, also support real-time ship monitoring and pollution prevention (Elsisi et al., 2025).

3.4. Integrated Smart Ecoport 5.0 Concept

The Integrated Smart Ecoport 5.0 framework represents a paradigm shift in sustainable port development by incorporating smart technologies, environmental priorities, and climate resilience within a unified system (Figure 2). Unlike traditional models that address operational efficiency and environmental impact in silos, this integrated concept acknowledges the interconnectedness of technological innovation, ecological integrity, and adaptive capacity.

At its core, the Smart Infrastructure pillar focuses on the digitalization of port operations. It emphasizes the use of real-time data systems, Internet of Things (IoT)-enabled logistics, and energy-efficient technologies to optimize operational performance and minimize resource consumption. These advancements not only improve cargo flow and terminal management but also contribute to the reduction of carbon footprints.

The second pillar, Environmental Sustainability, promotes circular economy principles and biodiversity-sensitive design. Ports are reimagined as ecological actors, implementing low-carbon operations, reusing materials, and adopting green infrastructure that harmonizes with natural ecosystems. This approach ensures that environmental goals are not secondary, but integral to port planning and function.

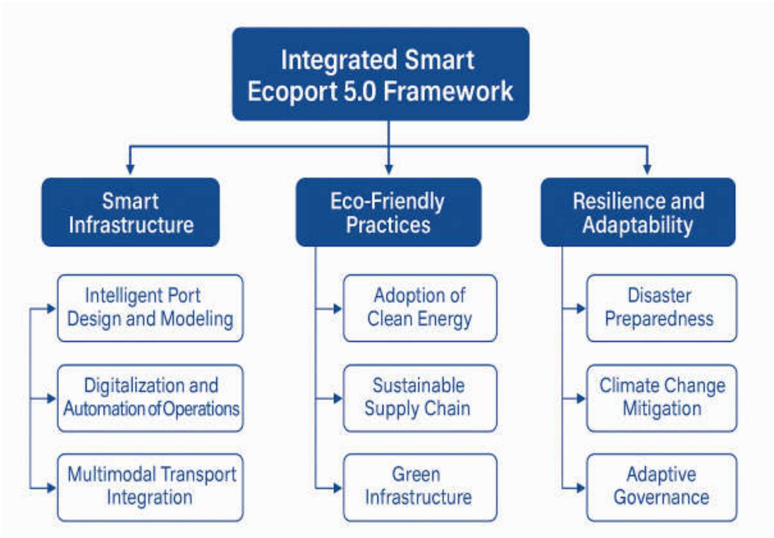


Figure 2. Integrated Smart Ecoport 5.0 Framework

The third component, Climate Resilience, addresses the increasing threat of climate-induced hazards. It integrates ecosystem-based adaptation strategies, modular infrastructure capable of withstanding extreme weather, and predictive early warning systems. These measures are essential for ensuring operational continuity amid rising sea levels, storm surges, and other disruptions.

Crucially, all three pillars are interwoven with cross-cutting innovations such as human-centric design, collaborative robotics (cobots), and ethical AI governance. These elements ensure that technological progress aligns with human values, inclusivity, and long-term sustainability goals.

As depicted in Figure 2, the Integrated Smart Ecoport 5.0 is not merely an assembly of smart solutions but a dynamic, resilient, and sustainable port ecosystem, designed to meet the evolving demands of global trade, climate adaptation, and social responsibility.

4. Implementation and Benchmarking of Global Smart Ports

The global adoption of the Smart Ecoport 5.0 paradigm reflects a growing commitment among major ports to integrate smart technologies with environmental sustainability and climate resilience. However, the level, focus, and maturity of implementation vary considerably across regions and operational contexts.

The Port of Rotterdam in the Netherlands serves as a global benchmark for port transformation initiatives. It demonstrates a comprehensive integration of digital infrastructure—such as digital twins and IoT-based real-time monitoring systems—with firm commitments to sustainability through hydrogen hubs, shore power, and circular economy initiatives. In terms of climate resilience, Rotterdam leads with adaptive planning frameworks and robust flood defense systems, including storm surge barriers (González-Cancelas, Martínez Martínez, et al., 2025; Suvadarshini & Dandapat, 2023).

Similarly, the Port of Singapore has prioritized automation and high-connectivity systems, as exemplified by the development of the Tuas Mega Port-an entirely automated terminal designed to consolidate national port operations. Enhanced by 5G technologies, artificial intelligence (AI), and big data analytics, Singapore's smart port infrastructure supports efficient logistics and real-time vessel traffic control. Its environmental efforts include LNG bunkering, solar power installations, and zero-waste targets. However, climate adaptation is still approached through conventional urban-coastal resilience strategies (Yau et al., 2020).

The Port of Hamburg in Germany has launched the SmartPort Initiative, combining ICT-based operational optimization with efforts to reduce CO_2 emissions. It also promotes onshore power supply systems and deploys early warning systems to address flood risks and rising sea levels. In contrast, the Port of Los Angeles in the United States focuses on port-wide digital optimization tools and electrification roadmaps. Through the Green Truck Program and investments in clean energy infrastructure, the port aims to reduce its carbon footprint. However, its resilience framework remains reactive, relying predominantly on post-disaster response protocols.

In China, ports such as Shenzhen and Ningbo-Zhoushan have adopted ambitious digitalization strategies. These include the deployment of 5G-based smart operations, autonomous cranes, blockchain logistics, and Automated Guided Vehicles (AGVs), which significantly enhance operational throughput (L. L. Li et al., 2021). On the environmental aspect, Shenzhen promotes electric tugboats and green corridor initiatives, although ecological and climate adaptation policies remain driven mainly by national coastal defense programs.

A synthesis of these implementation approaches is provided in Table 1, which summarizes each port's initiatives under three key dimensions: smart infrastructure, environmentally friendly practices, and climate resilience.

Recent developments in smart port technologies further reinforce these trends. For instance, the application of AI-based Port Logistics Metaverse Framework (PLMF) at Busan Port has led to significant operational improvements, including a 79% increase in ship punctuality and a notable rise in revenue (Sim et al., 2024). Similarly, the deployment of Industry 4.0 elements—such as Cyber-Physical Systems (CPS), IoT, cloud computing, and business analytics—has enhanced visibility, asset utilization, and response times in maritime logistics (Al-Fatlawi & Motlak, 2023; Min, 2022).

Port	Smart Infrastucture	Environmentally Friendly Practices	Climate Resilience & Adaptation
Rotterdam	Digital twin, AI logistics, sensor IoT	Hydrogen hub, shore power, circular economy	Flood barriers, adaptive planning
Singapore	Digital twin, Tuas Mega Port is fully automated container terminal being developed to consolidate Singapore's port operations and increase capacity.	LNG bunkering, solar power, zero waste targets	Integrated urban-coastal resilience
Hamburg	SmartPort Initiative, data-driven port ops	Onshore power, CO_2 reduction program	Early warning system for flood and sea level rise
Los Angeles	Port Optimization tool, electrification roadmap	Green Truck Program, clean energy infrastructure	Wildfire smoke & disaster recovery protocols
China (Shenzhen)	5G Port Operational , autonomous cranes, blockchain logistics	Electric tugboats, green corridors initiative	National policy-driven coastal defense upgrades

Table 1. Implementation and Benchmarking of Global Smart Ports

Taken together, these case studies highlight both the opportunities and disparities in global Smart Ecoport 5.0 implementation. While technological advancement is widespread, the alignment of smart systems with ecological and climate-adaptive frameworks remains uneven and context-dependent. Future progress will require stronger integration between infrastructure innovation, environmental policy, and resilience planning across port ecosystems.

5. Discussion: Highlighting the Novelty of Smart Ecoport 5.0

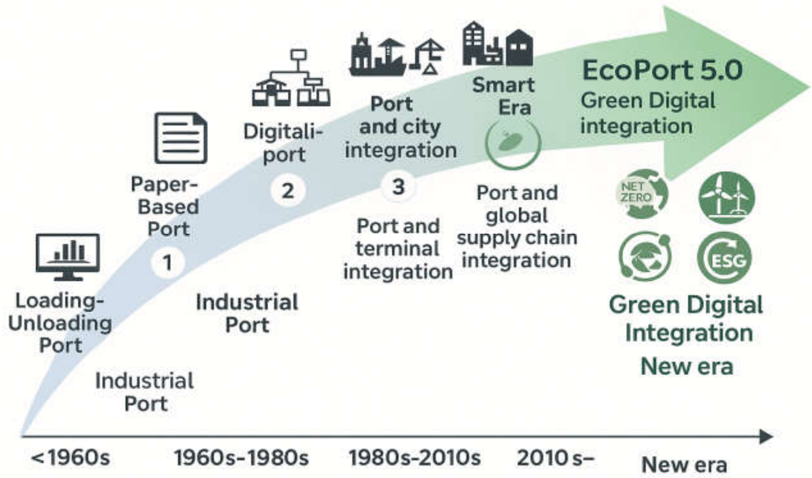
The concept of 'Smart Ecoport 5.0' proposed in this study brings significant innovation compared to previous definitions of smart ports or green ports. While most literature focuses on operational efficiency and emission reduction through digitalization and automation (Belmoukari et al., 2023; Min, 2022), the novelty of Smart Ecoport 5.0 lies in the deep integration of three main pillars: smart technology, sustainable green infrastructure, and disaster resilience, as mutually reinforcing elements to achieve holistic sustainability.

- **Holistic Integration vs. Specialized Focus**: Previous smart port concepts often identified seven business domains, namely operations, social, environmental, energy, human resources, safety, infrastructure, and technology (Makkawan & Muangpan, 2023).

However, Smart Ecoport 5.0 explicitly integrates eco (environmental) and resilience (disaster resilience) aspects as integral parts of the 'smart' framework, which are often considered separate or derivative in other models. For example, the emphasis on green logistics corridors (Bullock et al., 2023), the use of renewable energy on land and ships (Prousalidis & D'Agostino, 2023), and efforts to reduce emissions beyond operational efficiency demonstrate a deeper environmental commitment.

- **Disaster Resilience as a Central Pillar**: While many smart port frameworks prioritize the optimization of routine operations (Belmoukari et al., 2023), Smart Ecoport 5.0 distinguishes itself by positioning disaster resilience as a key criterion. This approach encompasses strategic planning that accounts for climate change and disaster-related risks, as evidenced by assessments of port adaptation requirements under extreme conditions. The emphasis on adaptive and responsive systems, such as in navigation and traffic management facing severe weather challenges (Chen et al., 2025), further underscores a stronger dimension of resilience.
- **Integrated Green Infrastructure**: Though green ports already exist, Smart Ecoport 5.0 embeds 'green infrastructure' as an integral element of port design and modeling. This includes not only the use of clean energy but also design approaches that minimize environmental impact and maximize natural ecosystems within and surrounding the port (Zhang et al., 2024). This goes beyond mere compliance with environmental regulations, aiming to create a port ecosystem that is more harmonious with nature.
- **Technology Synergy for Adaptive Sustainability**: Technologies such as AI, blockchain, and IoT are employed not solely to enhance operational efficiency but are intentionally leveraged to advance environmental sustainability and disaster resilience objectives (Dinh et al., 2024; Nguyen et al., 2023; Rekabi & Sazvar, 2025). For example, AI-based systems that predict vessel estimated time of arrival help reduce both waiting times and emissions, and machine learning-based drone sensors facilitate real-time emissions monitoring (Elsisi et al., 2025). These applications illustrate that technology serves as an enabler for sustainability and resilience, not just productivity.

Overall, the novelty of Smart Ecoport 5.0 lies in the premise that future ports must not only be smart in their operations but also inherently 'eco' and 'resilient'. This is achieved through the systematic and planned integration of technology, ecological principles, and risk mitigation strategies. As a result, this model offers a more comprehensive and future-proof framework for global port development.



Figures 3. Port Development Timeline: From the Conventional Era to EcoPort 5.0

Figure 3 and Table 3 represent the evolution of port functions and digitalization from the conventional models to the sustainable and globally integrated EcoPort 5.0 era. Initially, ports operated as paper-based facilities with limited functions focused on loading and unloading sites, moving towards industrial and logistics ports that began to implement limited digitalization. With technological advancements, ports became interconnected with terminals, cities, and global supply chains, giving rise to Smart Port 4.0, characterized by the adoption of Internet of Things (IoT) technology, big data, and automation. At a more developed stage, the concept of EcoPort 5.0 was added, which is not only smart and connected but also prioritizes sustainability, circular economy, and resilience to climate change, making it part of a global logistics system that is environmentally friendly and adaptive to future challenges.

Era/ Year	**Stages of Port Function Development**	**Digitalisation and Connectivity Phase**	**Key Features**
< 1960-an	Loading-Unloading Port	Paper-Based Port (1)	Manual, paper documents, focus on loading and unloading
1960s–1980s	Industrial Port	Digitalized Port (2)	With the advent of basic computer systems, industrial activity developed around the port.
1980s–2010s	Logistic Port	Port and Terminal Integration (3)	Logistics activities are increasing, with port integration with terminal management systems
2010–now	Smart Port 4.0	Port and City Integration (4) + Port and Global Supply Chain Integration (5)	IoT, Big Data, AI, ports as nodes in the global supply chain; integration with cities
2025 onwards	EcoPort 5.0	Green Digital Integration	Smart and green ports, environmentally oriented and resilient to climate change (Net-Zero)

Table 3. Key Features of Port Development Timeline: From the Conventional Era to EcoPort 5.0

6. Conclusion

This study has identified the key criteria that constitute the Smart Ecoport 5.0 concept: smart port design and modeling, clean energy implementation, supply chain digitalization and operational automation, as well as the integration of sustainable multimodal transport and adaptive port governance. Through a literature analysis and case studies of global ports, it is evident that Smart Ecoport 5.0 represents a significant evolution in port management. It surpasses conventional smart and green port paradigms by holistically integrating principles of environmental sustainability and disaster resilience into a smart technology framework (Belmoukari et al., 2023). The main novelty of this concept lies in the synergistic combination of digital-based operational efficiency, proactive green infrastructure, and robust disaster resilience capabilities, creating ports that are not only high-performing but also ecologically responsible and adaptive to crises.

7. Recommendations

Develop Adaptive Regulatory Frameworks: Governments and port authorities must develop regulations and policies that support the adoption of Smart Ecoport 5.0 technologies, including incentives for investments in renewable energy, green infrastructure, and disaster resilience systems (Mdanat et al., 2024; Tsvetkova et al., 2025).

Invest in Integrated Infrastructure: Significant investment is required in digital infrastructure (5G, IoT, AI), green infrastructure (cold ironing facilities, solar panels, wind turbines), and disaster resilience-enabling infrastructure (early warning systems, earthquake/flood-resistant designs) (Prousalidis & D'Agostino, 2023).

Foster Multistakeholder Collaboration: The establishment of strong forums and coordination mechanisms among government bodies, port operators, logistics companies, technology providers, and local communities is crucial for successful harmonization and implementation (Nasser et al., 2025; Sarabia-Jacome et al., 2020).

Enhance Human Resource Capacity: Training and skill development programs for the port workforce need to be adapted to the technological and operational requirements of Smart Ecoport 5.0, including expertise in data analysis, automated system management, and sustainability practices.

Conduct Continuous Benchmarking: Ports should regularly benchmark against global best practices in Smart Ecoport 5.0 to identify areas for improvement and adopt the latest innovations (Molavi et al., 2020)

Focus on Green Logistics Corridors: Promote the development of low-carbon distribution routes within and outside the port to integrate logistics efficiency with emission reduction goals (Bullock et al., 2023).

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