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SMART-PORT: A NEW PARADIGM FOR MANAGING SEAPORTS

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SMART-PORT: НОВА ПАРАДИГМА УПРАВЛІННЯ МОРСЬКИМИ ПОРТАМИ

The aim of this article is to substantiate the conceptual foundations of the "Smart Port" as a new paradigm for seaport management, to identify the key elements of this model, and to assess their impact on the formation of an adaptive, integrated port management model. Within the scope of the study, it was established that the "Smart Port" concept does not have a single standardized realization and implementation format, allowing ports to adopt varying levels of digital transformation-from partial automation of specific processes to the creation of fully integrated digital ecosystems. It has been demonstrated that an effective transition from a traditional functional-operational model to an adaptive, data-driven, and network-integrated management model requires a close alignment of technological innovations with the strategic objectives of the port, including reducing cargo handling time, improving the transparency and accuracy of management decisions, optimizing logistics flows, and ensuring energy efficiency. The key characteristics of the "Smart Port" concept have been identified as: digitalization of

operations through ICT, IoT, Big Data, and digital platforms; integration and interconnectivity of port systems; intelligent management through analytics and AI; operational autonomy; integration into global supply chains; and environmental orientation and energy efficiency. Within this study, the possibility of building an adaptive and integrated management model has been highlighted, focusing on the following "Smart Port" elements: digital infrastructure, integrated management systems, analytical-intelligent management core, automated and robotic systems, stakeholder interaction platforms, cybersecurity systems, and environmental and energy solutions. Accordingly, the value of the study lies in the systematic identification of development vectors for an adaptive port management model, reflecting the comprehensive transformation of port infrastructure and operations in the context of digitalization, integration, and sustainable development. Specifically, these vectors enable the formation of an efficient, transparent, technologically integrated, and environmentally responsible port management model, enhancing global competitiveness and ensuring the sustainable development of port infrastructure.

Метою статті є обгрунтування базових засад концепції "Smart Port" як нової парадигми управління морськими портами, а також визначення ключових елементів цієї моделі та їх впливу на формування адаптивної й інтегрованої системи управління портовою діяльністю. У межах дослідження встановлено, що концепція "Smart Port" не має стандартизованого формату реалізації та впровадження, що дозволяє портам обирати різні рівні цифрової трансформації — від часткової автоматизації окремих процесів до інтегрованих цифрових екосистем. Доведено, що ефективний перехід від традиційної функціонально-операційної моделі до адаптивної, орієнтованої на дані та мережні моделі управління потребує тісного зв'язку технологічних інновацій зі стратегічними цілями порту (серед яких скорочення часу обробки вантажів, підвищення прозорості та точності управлінських рішень, оптимізація логістичних потоків та забезпечення енергоефективності). Констатовано, що ключовими ознаками концепції "Smart Port" є: цифровізація діяльності через ICT, IoT, Big Data та цифрові платформи; інтегрованість та взаємозв'язок підсистем порту; інтелектуалізація управління за допомогою аналітики та AI; автоматизація операцій; інтеграція у глобальні ланцюги постачання; екологічна орієнтованість та енергоефективність. У дослідженні відмічена можливість побудови адаптивної, інтегрованої моделі управління морськими портами за фокусом на такі елементи "Smart Port", як: цифрова інфраструктура, інтегровані системи управління, аналітично-інтелектуальне ядро, автоматизовані та роботизовані системи, платформи взаємодії зі стейкхолдерами, системи кібербезпеки та еколого-енергетичні рішення. Цінність дослідження полягає в систематичному визначенні векторів розвитку адаптивної, інтегрованої моделі управління морськими портами, що відбиває комплексну трансформацію портової інфраструктури та операцій у контексті цифровізації, інтеграції та розвитку. Зокрема, окреслені вектори дозволяють створити ефективну, прозору, технологічно інтегровану та екологічно відповідальну модель управління портами, що підвищує їхню конкурентоспроможність на світовому рівні та забезпечує сталий розвиток інфраструктури.

Key words: use of digital technologies; intelligent environment; elements of the port ecosystem; optimization of operational processes; global supply chains.

Ключові слова: використання цифрових технологій; інтелектуальне середовище, елементи портової екосистеми; оптимізація операційних процесів; глобальні ланцюги постачання.

PROBLEM STATEMENT

At present, seaports in different countries are undergoing active transformation, driven by the shift from traditional transport and logistics hubs to complex multifunctional systems closely integrated into global supply chains. A major aspect of this transformation is the implementation of the "Smart Port" concept, which involves the use of digital technologies to create an intelligent environment where all elements of the port ecosystem-from berths and terminals to transport and information systems-interact in real time, ensuring optimization of operational processes and increasing their transparency.

The practical implementation of the Smart Port concept can be observed in leading ports worldwide, including the Port of Rotterdam, Port of Hamburg, Port of Valencia, Port of Singapore, Yangshan Deep-Water Port, Port of Busan, and Port of Los Angeles, where its adoption has already contributed to improved management efficiency, faster cargo handling, better accuracy in logistical coordination, and reduced vessel downtime. Ukrainian seaports are at various stages of digital transformation, and currently, the implementation of smart technologies is mostly fragmented, carried out through individual projects and initiatives rather than as an integrated systemic "Smart Port" model. Meanwhile, initial positive developments are already being observed, such as increased operational transparency, improved planning of transshipment processes, and optimization of document flow between terminals and transport companies.

Against this background, the "Smart Port" concept is not only at the stage of active practical testing and evolution but also represents a strategically important direction for the development of the port industry both globally and in Ukraine. However, the diversity of implementation practices demonstrates that "Smart Port" models depend on the specific characteristics of ports, their level of technological development, the institutional environment, and strategic priorities, which gives rise to a scientific problem-the absence of a generalized theoretical and methodological foundation.

Consequently, it necessitates the formation of unified approaches to Smart Port implementation, which will ensure consistency of digital solutions, integration of all participants in the port ecosystem, and the achievement of a synergistic effect from digital transformation.

Actual scientific researches and issues analysis. Currently, the features of developing a new paradigm for maritime port management — in particular, the implementation of digital technologies, automation of operations, and integration of environmental standards — as well as the general challenges of digitalizing the transport sector, are actively explored in the works of Kyryllov V.Yu., Kyryllov O.V., Mahamadov O.R. [4], Kyryllova O., Kyryllova V., Mahamadov O., Romakh V. [4], Ki Jun W., Lee M.K., and Young Cho J. [6]. At the same time, despite a significant number of studies dedicated to the digitalization of the transport industry, the issue of forming a comprehensive paradigm for maritime port management based on the Smart Port concept remains insufficiently developed, which considerably complicates the implementation of integrated development strategies and the optimization of port operations.

RESEARCH AIM

The objective of this paper is to substantiate the conceptual foundations of the "Smart Port" as a new paradigm for seaport management, to identify the key elements of this model, and to assess their impact on the formation of an adaptive, integrated approach to port operations management.

MAIN FINDINGS OF THE RESEARCH

In this study, the Smart Port concept is formalized based on the provisions of the International Maritime Organization (IMO) (regulations on safe and sustainable port development, digitalization of supply chains, and integration of smart solutions into port infrastructure); the Asian Development Bank (ADB); and the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP), as well as the recommendations of the International Association of Ports and Harbors (IAPH) (implementation of intelligent technologies and environmental sustainability); the European Commission (EU — Blue Growth and Digital Ports) (development of digital infrastructure and integration of IoT, Big Data, and AI); and UNCTAD (digital transformation of logistics and transport chains and integration of ports into global trade networks) [1—2; 5; 9]. This concept represents a new paradigm for seaport management, grounded in the integration of digital technologies, the intellectualization of processes, and a systemic approach to the development of the port ecosystem. Notably, according to the outlined concept, "Smart Port":

1. Demonstrate operational efficiency, are technology-driven, resilient to changes and crises, enhance the safety of technological operations, are energy-efficient, and pursue sustainable development (ADB [1]);

2. Aim to handle port assets and conduct port operations while optimizing cargo flows and vehicle movements through the use of new and advanced technologies (ESCAP [2]);

3. Have established a unified information environment to coordinate all processes and enable rapid data exchange among all participants in the supply chain (IMO, IAPH).

Given its significant relevance, the experience of developing "Smart Port" is currently widespread in leading seaports worldwide.

Notably, in the European region, the "Smart Port" concept as a new paradigm for seaport management has been a highly systematic approach since the early 2010s and continues to evolve actively. In practice, this is reflected in the implementation of comprehensive digital solutions in leading European ports. For instance, at the Port of Rotterdam, projects under the SmartPort brand began to be systematically implemented around 2012—2015 as part of a strategy for digitalization and the integration of digital traffic and infrastructure management systems; at the Port of Hamburg, the first major steps toward creating an IoT platform and digital infrastructure date back to 2018—2019, when the first sensor monitoring systems and digital services were introduced; and at the Port of Valencia, major digitalization projects, including the deployment of a 5G network as a key element of the Smart Port, were officially launched in 2024—2025 (see Table 1).

Table 1. Examples of "Smart Port" concept implementation in European region

Seaports implementing the concept	Key components defining the "Smart Port" framework	Results of smplementation
Port of Rotterdam	Digital twin of the port; IoT sensors for monitoring water, traffic, and infrastructure; Artificial Intelligence for predicting vessel arrival times (ETA); Autonomous transport systems	Improved port operational efficiency, optimized logistics flows, reduced cargo handling time, enhanced transparency and accuracy of management decisions
Port of Hamburg	“Smart roads” and traffic sensors; real-time management of vessel and land transport traffic; integration of port and urban infrastructure	Enhanced traffic safety and controllability, integration of the port into the urban logistics system, improved operational planning efficiency
Port of Valencia	Deployment of 5G technologies for high-speed data exchange; digital port management platforms (Port Community System, terminal platforms); emission monitoring systems; tools to increase energy efficiency and operational transparency (Digital Twin, BI, KPI dashboards)	Reduced emissions and energy consumption, improved operational transparency, optimized logistics, enhanced resource planning, decreased cargo handling time

Source: compiled according to the [7—8].

In the Asian region, the Smart Port concept, as a new paradigm of maritime port management, is also being actively implemented in leading port hubs, demonstrating various aspects of digital transformation. Specifically, at the Port of Singapore, the pursuit of deep automation and digital integration was established as early as the beginning of the 2010s, with stages of large-scale transformation accompanied by the development of forecasting systems and integrated platforms in 2015—2017, followed by further expansion as part of the Tuas Mega Port construction. At Yangshan Deep-Water Port, container terminal automation projects and the implementation of IoT tools began around 2016—2018, ensuring a high degree of operational autonomy at the terminals. At the Port of Busan, the first implementations of smart technologies and integrated planning systems date back to 2017—2018, with subsequent expansion linked to the creation of AI-oriented forecasting and optimization models. Thus, although Asian Smart Port initiatives started somewhat later, they quickly became a significant component of management strategies within global logistics networks (see Table 2).

In the United States, the gradual implementation of Smart Port concept elements also began around 2012—2014, although this process is currently less centralized and formalized compared to leading European or Asian hubs. The primary role in the digital transformation of American seaports is played by major port complexes on the West Coast — the Port of Los Angeles and the Port of Long Beach — which are implementing comprehensive digitalization, automation, and environmental optimization technologies (see Table 3).

Table 2. Examples of "Smart Port" concept implementation in Asian region

Seaports implementing the concept	Key components defining the "Smart Port" framework	Results of smplementation
Port of Singapore	Fully automated Tuas Mega Port; AI-based ETA and resource allocation systems; 5G connectivity and digital data platforms (digitalPORT@SG); blockchain systems for customs clearance	Faster vessel and cargo turnover, reduced delays at logistics junctions, increased operational efficiency at the global level, and maintenance of its status as one of the world's most technologically advanced ports
Yangshan Deep-Water Port (China)	Automated guided vehicles (AGVs); robotic cranes and IoT systems; weather forecasting systems for operational adaptation	Significant reduction in container handling time, optimization of operations without human intervention, increased throughput capacity, and enhanced resilience to weather-related risks
Port of Busan	Automated crane systems; deeply integrated AI and IoT systems; development of autonomous container terminals	Improved terminal productivity and flexible operational planning, as well as the development of new collaboration models between equipment and data management

Source: compiled according to the [1; 6; 9].

Table 3. Examples of "Smart Port" concept implementation in United States

Seaports implementing the concept	Key components defining the "Smart Port" framework	Results of smplementation
Port of Los Angeles	Port Optimizer: digital platform for real-time management of vessel and container traffic; IoT sensors for monitoring traffic, berths, and infrastructure; analytical tools for vessel arrival forecasting and terminal operations optimization; integration with environmental monitoring systems.	Faster vessel and cargo handling, optimized terminal operations, improved decision-making accuracy, enhanced operational transparency, and reduced emissions and energy consumption
Port of Long Beach	Digital container traffic planning systems and integrated terminal availability data; IoT platforms for infrastructure and transport monitoring; analytics for congestion forecasting and operations optimization; joint digital solutions with Port of Los Angeles for green shipping corridors	Increased throughput capacity, optimized transport flows and resource allocation, reduced downtime, improved operational efficiency, and strengthened environmental performance through "green" initiatives

Source: compiled according to the [7—9].

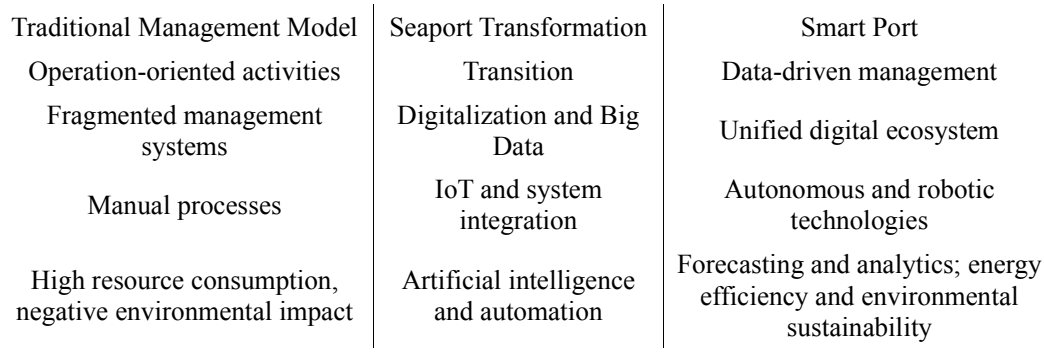

Figure 1. Conditions for the transition from a traditional functional-operational model to an adaptive, data-driven, and network-based paradigm of seaport management

Source: compiled according to the [4; 7—9].

Ukrainian ports are at different stages of digital transformation. The implementation of smart technologies is occurring gradually, primarily through individual projects or initiatives, including the introduction of electronic document management, automation of specific processes, monitoring and telemetry systems, and digital services for participants in logistics chains.

The findings indicate that the "Smart Port" concept does not have a single standardized implementation model — ports may adopt a wide range of digital solutions, from partial automation of specific processes to the creation of fully integrated digital ecosystems.

Transitioning to the analysis of the content of the outlined practices, we agree with the view of Ki Jun W., Lee M.K., and Young Cho J. [6] that the development of a "Smart Port" requires a shift from a traditional functional-operational model to an adaptive, data-driven, and network-integrated port management model. TFor this purpose, it is necessary to align technological innovations with strategic objectives, including reducing cargo handling time, increasing the transparency and accuracy of management decisions, and optimizing logistics and energy efficiency. In essence, the following can be identified as the key features of the outlined concept [3—5; 9]:

1. Digitalization of port activities through the implementation of information and communication technologies, the Internet of Things, big data, and digital platforms to ensure real-time data collection, processing, and exchange.

2. Enhanced integration and interconnectivity of systems, enabling the unification of port infrastructure elements — from operational processes to management levels — into a single information environment and their synchronization with external logistics chains.

3. Intellectualization of management, implemented through the use of analytical tools and artificial intelligence technologies to support decision-making, forecasting, and optimization of port operations.

4. Automation and autonomy of port operations, namely the application of robotic systems, automated terminals, and unmanned vehicles to increase productivity and reduce operational costs.

5. Network integration into global supply chains, ensuring effective interaction with shipping companies, transport operators, customs authorities, and other stakeholders based on digital platforms.

6. Environmental orientation and energy efficiency, achieved through the implementation of resource monitoring and management technologies aimed at reducing emissions, optimizing energy consumption, and ensuring sustainable development.

A more detailed description of the conditions for the transition from a traditional functional-operational model to an adaptive, data-driven, and network-based paradigm of seaport management is presented in Figure 1, which schematically illustrates the interconnections between the key components of the Smart Port concept and the mechanisms of their integration into a unified ecosystem.

From this perspective, the following have been identified as the core elements of the Smart Port concept that determine such a transition: (1) port digital infrastructure; (2) integrated management systems; (3) an analytical and intelligent management core; (4) automated and robotic operational systems; (5) digital platforms for stakeholder integration; (6) cybersecurity and data protection systems; and (7) environmental and energy solutions. The generalized content and key characteristics of these elements are systematized in Table 4.

The systematization of the core "Smart Port" elements (Table 4) allows for the identification of their functional interactions and the determination of key vectors for developing an adaptive, integrated, and sustainably oriented port management model, which include:

— Transition to a data-driven decision-making model based on digital technologies, Big Data, and analytics;

— Formation of a unified information space and coordination of operational, logistical, and managerial processes within the port and with external supply chains;

— Implementation of forecasting, modeling, and optimization systems based on artificial intelligence;

Table 4. Characteristics of the content and core elements of the "Smart Port"

Core Smart port element	General content of the "Smart Port" element	Common features of "Smart Port" elements
Digital port infrastructure	A set of ICT solutions (data transmission networks, IoT, cloud services, digital platforms) ensuring uninterrupted data flow within the port ecosystem.	• Real-time data processing; • Scalability and flexibility of infrastructure; • System interoperability; • High throughput of information flows
Integrated management systems	Digital systems (PCS, TOS) coordinating operational, logistical, and administrative port processes.	• End-to-end process integration; • Synchronization of information flows; • Operational transparency; • Reduction of transaction costs
Analytical-Intelligent management core	A set of analytical tools (Big Data, AI, BI) supporting decision-making, forecasting, and optimization of port operations.	• Predictive and proactive management; • Data-driven decision-making; • Scenario modeling capabilities; • Resource optimization
Automated and robotic operational systems	Technological solutions (automated terminals, robotic equipment, autonomous transport) performing port operations with minimal human intervention.	• High level of process automation; Increased operational productivity and accuracy; • Reduced operational costs; • Enhanced occupational safety
Digital stakeholder sntegration platforms	Platforms facilitating interaction between the port and supply chain participants (carriers, customs, logistics operators).	• Networked interaction and openness; • Unified information space; • Reduced time for coordination; • Enhanced transparency and trust
Cybersecurity and data protection systems	A set of organizational and technical measures to protect information resources and digital infrastructure.	• Ensuring data confidentiality, integrity, and availability; • Resilience to cyber threats; • Continuous system operation; • Compliance with information security standards
Environmental and energy solutions	Technologies and management approaches to improve energy efficiency and reduce the port's environmental impact	• Monitoring and optimizing energy consumption; • Reduction of emissions and pollution; • Integration of renewable energy sources; • Focus on sustainable development principles

Source: compiled according to the [7—9].

— Enhancement of port process automation and deployment of robotic and unmanned technologies;

— Development of digital collaboration platforms ensuring transparent and continuous interaction among supply chain participants;

— Creation of a secure digital environment for port operations;

— Focus on reducing environmental impact, optimizing resource consumption, and implementing sustainable development principles.

CONCLUSIONS

Within the scope of the study, it has been established that the "Smart Port" concept does not have a single standardized implementation format, allowing ports to adopt different levels of digital transformation-from partial automation of individual processes to the creation of fully integrated digital ecosystems. It has been demonstrated that an effective transition from the traditional functional-operational model to an adaptive, data-driven, and network-integrated management model requires a close alignment of technological innovations with the port's strategic objectives, including reducing cargo handling time, enhancing the transparency and accuracy of management decisions, optimizing logistics flows, and ensuring energy efficiency.

It has been noted that the key characteristics of the "Smart Port" concept include: digitalization of operations through ICT, IoT, Big Data, and digital platforms; system integration and interconnectivity within the port; intelligent management using analytics and AI; automation and operational autonomy; networked integration into global supply chains; and environmental orientation and energy efficiency. Within the framework of this study, the possibility of building an adaptive and integrated management model has been highlighted, focusing on core "Smart Port" elements such as digital infrastructure, integrated management systems, an analytical-intelligent management core, automated and robotic systems, stakeholder interaction platforms, cybersecurity systems, and environmental and energy solutions.

Accordingly, the value of this study lies in the systematic identification of development vectors for an adaptive port management model that reflects the comprehensive transformation of port infrastructure and operations in the context of digitalization, integration, and sustainable development. Specifically, these vectors enable the formation of an efficient, transparent, technologically integrated, and environmentally responsible port management model, enhancing ports' global competitiveness and ensuring sustainable infrastructure development.

The prospects for further research lie in the development of standardized models for implementing the "Smart Port" concept.

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