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SMART PORT CLUSTERS AS A MODERN TOOL FOR THE DEVELOPMENT OF THE GLOBAL TRANSPORT COMMUNICATIONS SYSTEM AND A STRATEGIC VECTOR FOR THE POST-WAR RECOVERY OF UKRAINE'S PORT INDUSTRY

The article explores Smart Port clusters as a modern tool for the development of the global transportation system and a strategic vector for the post-war restoration of Ukraine's port infrastructure. The study aims to substantiate the strategic role of Smart Port Clusters within the global transport network, assess their development prospects, and evaluate their integration into Ukraine's port infrastructure, considering contemporary technological trends and post-war recovery challenges. The focus is on analyzing innovative technologies such as digitization, automation, and the integration of digital platforms that enhance port operations, improve cargo flow management efficiency, and ensure ecological sustainability. The study also examines the implementation of artificial intelligence (AI), big data, the Internet of Things (IoT), blockchain, and digital twins to optimize and integrate transport processes in real time. Global trends in the development of smart port clusters are analyzed, including the use of autonomous vessels, robotic cargo handling systems, and automated dispatching systems. Cases from leading ports worldwide, such as Rotterdam, Singapore, and Hamburg, demonstrate the effectiveness of digital technologies in improving the competitiveness of port operations. Furthermore, the article highlights the potential of Smart Port Clusters in the post-war restoration of Ukraine's port infrastructure. The study identifies that the adoption of modern digital technologies can significantly accelerate port recovery, enhance their competitiveness at the international level, and attract investments. It also offers recommendations for integrating Ukrainian ports into global transport networks through the use of Smart Cluster models. The findings of the study show that Smart Port Clusters can significantly improve port operations by reducing operational costs, optimizing cargo flows, and decreasing environmental impact. The novelty of the work lies in investigating the potential of these clusters for restoring Ukraine's economy through their integration into global technological ecosystems. As a result, the article confirms the importance of Smart Port Clusters as a key tool for modernizing transport infrastructure, enhancing port resilience, and integrating ports into the global transport ecosystem. The proposed recommendations can be used in the development of national strategies for the port sector's recovery in the post-war period. This study is a significant contribution to the development of the Concepts of Smart Ports and Smart Port Clusters, as well as to the integration of cutting-edge technologies into transport systems. The results can inform the formulation of a National Strategy for the development of Smart Ports and Smart Port Clusters, including legislative initiatives, funding for investment projects, and the development of international partnerships. The implementation of Smart Port Clusters will reduce operational costs, increase productivity, and lower environmental impact, thereby contributing to the development of Ukraine's economy, particularly in the port sector.

Key words: *Smart Ports, Port Clusters, Intellectual Port Clusters, Smart Port Clusters, Port Digitalization, Port Operations Automation, Artificial Intelligence In Ports, Big Data In Transportation, Internet Of Things (Iot) In Ports, Green Technologies In Ports, Port Development Strategies, Freight Transportation.*

Formulation of the problem. The creation of SMART PORT Clusters has become a key direction in the transformation of the global transport system, which determines the competitiveness of port complexes in the XXI century. The integration of digital technologies, artificial intelligence, the Internet of Things (IoT), and automated transport systems contributes to improving the efficiency of port operations, optimizing international freight flows, and reducing the carbon footprint. Specifically, SMART PORT Clusters ensure higher cargo processing speeds, better interaction among participants in

logistics chains, and improved environmental conditions in port areas.

In this regard, there is an important scientific task to develop effective models and strategies for implementing SMART PORT Clusters in the global transport infrastructure. Contemporary scientific research confirms that the formation of such clusters allows ports to adapt to changes in global trade, ensuring a high level of resilience to crises and geoeconomic challenges. This not only promotes economic growth but also strengthens the geopolitical and economic stability of countries that use such cluster models to integrate their ports into international transport networks [1, p. 361-362; 2].

The transformation of the port industry through the creation and development of SMART PORT Clusters is an essential component of modern transport system development strategies [1, p. 361-362; 2]. In the context of post-war reconstruction of Ukrainian ports, this task becomes particularly relevant, as intelligent technologies can become the foundation not only for economic recovery but also for infrastructure rehabilitation. Increasing the technological efficiency of ports and adapting them to the latest international standards is essential for the recovery and integration of Ukrainian ports into global transport networks.

Analysis of recent research and publications. The development of SMART PORT Clusters is focused on integrating digital technologies, automating port processes, and applying artificial intelligence to optimize the functioning of ports within global transport networks. In work [1, p. 361-362], the SMART PORT Cluster concept is presented as an innovative approach to the development of port infrastructure and its integration into the global transport system. The key advantages of this model are identified, including enhanced efficiency, environmental safety, and the competitiveness of port complexes.

The publication [2] explores the prospects of implementing SMART clusters in Ukraine's port system as a tool for modernizing maritime transport hubs in line with global trends in digitalization, automation, and environmental sustainability. The key structural elements of port SMART clusters are defined, including digital management platforms, automated transport corridors, environmental monitoring systems, multimodal integration, and cybersecurity measures. The strategic role of SMART clusters in strengthening the competitiveness of Ukrainian ports, their integration into the global economy, and the creation of a sustainable transport system is substantiated, taking into account post-war challenges and the need for critical infrastructure recovery.

The concept of SMART PORTS is the subject of numerous scientific studies that analyze global trends in the implementation of intelligent technologies in port infrastructure. For instance, the article [3, p. 81-90] examines the main stages of development of this concept and the practical aspects of its implementation in international port practice. Works [4, p. 82-85; 5, p. 63-72] provide a detailed analysis of modern technologies and their implementation in leading ports worldwide.

The research [6, p. 28] emphasizes the significance of the SMART PORT concept in the context of Industry 4.0. Specifically, the possibilities of using the Internet of Things, cloud computing, and cybersecurity measures in maritime operations are discussed, contributing to the enhanced efficiency of port management.

Publication [7, p. 654-662] is dedicated to the automation of technological processes within the development of green and SMART ports. Using the example of the Wismar seaport, it shows how the digitalization of operations can effectively combine with environmental initiatives, reducing the carbon footprint and optimizing transport flows.

The article [8, p. 5-22] addresses the issue of standardizing digital services within the «Port of the Future» concept, particularly analyzing relevant technologies and information systems that ensure the unification of digital interactions between ports.

Thus, contemporary scientific research confirms the strategic importance of SMART PORTS and SMART PORT Clusters as key elements of the global transport system. They contribute to enhancing the competitiveness of ports, adapting to the challenges of international trade, reducing environmental impact, and ensuring the resilience of port infrastructure in crisis situations.

Task statement. The aim of the research is to substantiate the strategic role of SMART PORT Clusters in the global transport system, assess their development prospects, and explore the possibilities of their integration into Ukraine's port infrastructure, considering current technological trends and post-war recovery challenges.

To achieve the set goal, the following tasks have been defined:

1. To systematize the conceptual approaches to the formation of SMART PORT Clusters, defining their key structural elements, technological foundation, and principles of operation.

2. To analyze global trends in the development of SMART PORT Clusters and their impact on the efficiency and resilience of port systems.

3. To define the role of SMART PORT Clusters in enhancing the competitiveness of ports, their integration into international transport networks, and their adaptation to changes in the global economy.

4. To substantiate the prospects for the implementation of SMART PORT Clusters in Ukraine, taking into account post-war challenges, the need for modernization of critical infrastructure, and ensuring its sustainable development in the context of digitalization and ecological transformation.

Outline of the main material of the study. The modern port industry is undergoing significant changes driven by global digitalization, automation, and the need to enhance the efficiency of transport processes. In this context, the concept of SMART PORT Clusters becomes not only a logical stage in the evolution of ports but also a strategic tool for adapting to the new challenges of the global transport infrastructure.

The formation of Intelligent Port Clusters reflects a shift in the approach to organizing port activities. Instead of the traditional model of individual terminals and transport hubs, an integrated digital ecosystem emerges, based on the use of artificial intelligence, big data analytics, automated management systems, and real-time interaction.

Next, we will sequentially examine the key aspects of the creation of Intelligent Port Clusters, their role in enhancing port operations' efficiency, as well as global trends in the development of this concept. Additionally, we will analyze the integration of such clusters into international transport networks, particularly in the context of post-war reconstruction of Ukraine's port infrastructure, the need for modernization of critical infrastructure, and adaptation to modern technological requirements.

1. The Creation of Intelligent Port Clusters (Smart Port Clusters) as a New Stage in the Evolution of the Port Industry.

The development of the global port industry is on the verge of a technological breakthrough driven by global digitalization, automation, and the growth of maritime transport volumes. Intelligent Port Clusters are creating a new level of port operations, where digital technologies, artificial intelligence (AI), big data and automated systems interact within a unified innovative ecosystem [1, p. 361-362; 2].

An Intelligent Port Cluster is a complex dynamic system that evolves in real-time through the integration of advanced digital, technological, and managerial solutions. It creates an innovative environment for optimizing technological processes, increasing productivity, reducing operational costs, ensuring

environmental sustainability, and enabling effective interaction among all cluster participants, thus facilitating their integration into global transport networks.

The composition of an Intelligent Port Cluster includes:

– port infrastructure (terminals, docks, warehouses, transshipment complexes, energy and environmental facilities, renewable energy objects);

– transport hubs (ports, railway stations, etc.);

– communication routes (motorways, railway tracks, shipping lanes, intra-port routes for cargo and vehicle movements);

– digital management platforms (systems for vessel arrival monitoring, automated dispatch management, predictive analytics, optimization of port operations);

– transport operators (shipping companies, freight forwarding enterprises, customs and regulatory authorities, insurance companies);

– information and technological services (cloud computing, blockchain platforms, Internet of Things (IoT) systems, digital twins of port infrastructure, artificial intelligence (AI), autonomous systems, cargo flow and vessel arrival management systems).

These elements interact in real-time, enabling the optimization of cargo flows, reducing vessel downtime, increasing productivity and minimizing human error.

Key components of Smart Port Clusters:

– digital management technologies – the implementation of automated dispatch systems, vessel arrival management, terminal performance monitoring;

– automated cargo handling systems – robotic cranes, autonomous loaders, «smart» conveyors, unmanned ground and water transport vehicles;

– predictive analytics technologies – the use of AI and Big Data for predicting peak loads, allocating port resources and managing risks;

– decentralized data exchange platforms – the integration of blockchain solutions for secure and transparent data exchange between ports, operators, and regulators [5, p. 69-70].

Intelligent Port Clusters enable the creation of a global digital transport network, where information about each cargo, vessel, and operation is available in real-time. This opens up new opportunities for continuous improvement of technological processes and operations, automation of document flow, reduction of operational costs, and lowering of environmental impact.

Thus, an Intelligent Port Cluster is not just a high-tech system for managing port operations but a developed innovation ecosystem, where the interaction of

infrastructure objects, digital platforms, and business entities creates a new level of sustainable and efficient port operations within the global transport system.

Smart Port Clusters establish a new paradigm for port development, where traditional port management models [9] are replaced by models based on the integration of interconnected intelligent and high-tech solutions. This not only enhances the efficiency of port production activities but also enables ports to become hubs of data and innovation, allowing them to not just respond to changes but actively predict them, adapt to future challenges, and set new trends in the global transport ecosystem.

2. Global Trends in the Development of Smart Port Clusters.

The global transport system is undergoing a massive transformation, with key driving forces being digitalization, automation, and sustainable development. In the context of rising global trade, increasing cargo flows, and the need to enhance port operational efficiency, Smart Port Clusters are becoming the foundation for the future development of port infrastructure.

Global Megatrends in the Development of Smart Port Clusters:

– automation and autonomous technologies. The active development of autonomous shipping, robotic terminals, and the use of drones for monitoring and technical diagnostics of port infrastructure significantly reduces costs and accelerates cargo handling. In the ports of Singapore and Rotterdam, autonomous container ships and autonomous port cranes are already being tested and operated [3, p. 78-83];

– artificial intelligence (AI) and Big Data. Intelligent analytical systems based on AI are used for predicting peak loads, optimizing terminal operations, managing vessel calls, and reducing idle times. In the port of Hamburg, AI algorithms, by optimizing resource allocation, allow reducing the average container transshipment time by 30 %;

– blockchain and data transparency. Decentralized technologies ensure instant and secure data exchange between all participants in the Port Cluster, from shipping companies to customs authorities. For instance, the «TradeLens» system, developed by «Maersk» and «IBM», ensures transparent supply chain management, reducing bureaucratic barriers and accelerating customs clearance [5, p. 69-70]. This system is already used by over 300 ports worldwide;

– green port infrastructure. Environmental sustainability is becoming a priority for leading ports. The implementation of renewable energy sources, electric handling equipment, and emission reduction systems significantly reduces the environmental impact. For example, the Port of Los Angeles plans to become fully «green» by 2030;

– 5G and the internet of things (IoT). 5G technology ensures instant data exchange between all components of the port ecosystem, while IoT sensors enable real-time tracking of cargo movement, container conditions, and equipment performance [4, p. 85].

The global leaders in the development of Smart Port Clusters today are recognized as:

Singapore – a global leader in Smart Ports, where the «Next Generation Port» concept is implemented, involving full digitalization and automation of the port.

Rotterdam – a port that actively integrates blockchain, AI, and autonomous technologies to enhance terminal efficiency.

Hamburg – an example of a «Smart Port» with integrated digital platforms for real-time cargo flow management.

Shanghai – the world's largest container port, which employs robotic terminals and AI analytics to increase productivity [5, p. 71].

The development of Smart Port Clusters has become an integral part of the global integration of maritime transport, forming a unified digital infrastructure with continuous data exchange. Amid the dynamic growth of international trade and rapid transformations in the global economic environment, Smart Port Clusters ensure flexibility, efficiency and sustainable development of the global transport system.

3. The Role of Smart Port Clusters in the Global Transport Ecosystem.

Smart Port Clusters play a crucial role in enhancing the efficiency of the global transport system, contributing to the optimization of cargo flows, reducing turnaround times, and lowering transportation costs. As stated in the publication [3, p. 80-93], the creation of unified digital platforms for managing port processes ensures a new level of coordination between all participants in the transport chain.

The main advantages of Smart Port Clusters for the global transport system:

– acceleration of cargo handling and reduction of delays. The implementation of automated and robotic solutions in the world's largest ports allows reducing the average processing time for container ships by 30-50 %. For example, in the Port of Rotterdam, the use of a Digital Twin and AI analytics system has reduced vessel downtime, while in the Port of Shanghai, robotic cranes have decreased the container handling time from 20 to 7 minutes;

– reduction of transportation costs and increased transparency. Blockchain and digital platform technologies, such as «TradeLens», facilitate efficient document flow and minimize administrative expenses. According to research, the use of blockchain can reduce logistics costs by 15 % by eliminating unnecessary intermediary operations and speeding up customs clearance;

– environmental efficiency and reduction of CO_2 emissions. Smart Port Clusters play an important role in the decarbonization of the global transport system. As noted in the paper [3], integrating green energy, using electric handling equipment, and traffic forecasting analytics can reduce CO_2 emissions in ports by 20-40 %. For example, the Port of Long Beach is actively implementing «Shore Power Systems» that allow vessels to connect to onshore power instead of operating on diesel generators [4];

– global synchronization of transport flows. Smart Port Clusters contribute to the global coordination of maritime, rail, and road cargo flows, providing a unified digital system for managing shipments. Specifically, the Port of Hamburg has developed the «Smart Logistics Hub» system, which synchronizes vessel arrival times, rail terminal operations, and the distribution of goods among regional logistics centers [5].

Thus, the formation of Smart Port Clusters opens a new era in the development of the transport industry. As stated in works [1, 2], Smart Port Clusters will become the foundation for creating a global digital transport network, integrating maritime, road, rail, and air transportation into a single system.

4. Smart Port Clusters as a strategic direction for post-war reconstruction of the national transport system and its integration into the global transport network.

The war has significantly altered the logic of the maritime industry, requiring not only the physical reconstruction of infrastructure but also a rethinking of approaches to management, security, and technological development of port complexes.

Considering the new challenges, the key strategic directions for Ukraine include:

– reconstruction of ports with modern digital technologies. The rebuilding of port terminals should be based not only on physical reconstruction but also on the implementation of innovative digital solutions to enhance efficiency. In particular, this includes intelligent automated cargo flow management systems, artificial intelligence, and IoT solutions, which are already actively used in leading global ports such as Singapore and Rotterdam [4];

– development of multimodal transportation. Strengthening the connections between maritime, river, rail, and road transport will contribute to diversifying transport routes and enhancing supply chain resilience [10];

– creation of safe transport corridors and shipping routes. To ensure the safety and efficiency of transport, satellite and drone monitoring systems should be implemented to identify hazardous areas, and blockchain systems should be launched for route verification and risk management, similar to the Maersk-IBM TradeLens platform [5];

– expanding Ukraine's integration into international transport corridors. Post-war Ukraine will have a unique opportunity to strengthen its role in global transport networks:

a) Caspian-Black Sea route of the New Silk Road – including Ukrainian ports in this route will facilitate the recovery of exports through Georgia, Azerbaijan, and Kazakhstan;

b) expansion of cooperation with the EU – the creation of digital transport platforms for integrating Ukrainian ports into the Trans-European Transport Network (TEN-T) [3];

– creating a safe environment for investment. Post-war recovery requires attracting international investors and partners. This will be possible through the implementation of transparent port cluster management mechanisms and integration into European transport networks [4]. The development of Smart Port Clusters could become a priority for international financial support, particularly through:

a) EU and World Bank funds, which are already financing infrastructure projects in Ukraine;

b) private investments through the involvement of leading port operators (A.P. Moller-Maersk, DP World, Hutchison Ports) in the creation of innovative container terminals based in Ukrainian ports;

– Environmental modernization. The restoration of Ukraine's port infrastructure must comply with the principles of «green» development, including the use of renewable energy and environmentally friendly technologies in the transport sector [5].

Conclusions.

1. The creation of Smart Ports and Smart Port Clusters is an important step in the development of global port infrastructure, achieved through the integration of digital technologies, automation, and the use of advanced artificial intelligence systems, big data, and the Internet of Things. This enhances efficiency, ensures the flexibility of port operations, optimizes cargo flows, reduces operational costs, and minimizes the environmental impact of ports. Such

changes create the foundation for stable development and integration of ports into global transport networks.

2. Smart Port Clusters contribute to the development of the global transport system by significantly reducing cargo handling times, lowering transportation costs, and improving transparency in data exchange processes. The use of technologies such as blockchain, robotic systems, and autonomous cargo handling equipment improves coordination between all participants in the supply chain and increases the efficiency of international trade.

3. Given global environmental challenges, Smart Port Clusters play a significant role in reducing CO_2 emissions and ensuring the environmental efficiency of port operations. The integration of renewable energy sources, electric cargo handling equipment, and the application of green technologies help reduce the environmental impact of ports on the surrounding environment.

4. The implementation of Smart Ports and Smart Port Clusters concepts will not only contribute to the recovery of Ukraine's ports but will also create a competitive, technologically advanced transport system integrated into the global market. Ukraine has all the prerequisites to become a regional leader in the field of smart port technologies and modern transport strategies in the post-war perspective.

Further research in the highlighted direction should:

– include a comprehensive assessment of the impact of Smart Port Clusters on the economic efficiency of port operations, considering not only operational costs but also their influence on the growth of transit traffic, reduction in cargo handling time, and improvement in the efficiency of port capacity utilization;

– study the environmental impact of Smart Port Clusters on the surrounding environment, particularly on the condition of port areas, including the analysis of the possibility of reducing harmful gas emissions, preserving biodiversity, and implementing environmental monitoring systems;

– focus on the development of a National Strategy for the development of Smart Ports and Smart Port Clusters in Ukraine. This would include the creation of legislative initiatives, ensuring the financing of investment projects, and the development of international partnerships for integrating Ukrainian ports into global intelligent transport networks, which will allow attracting additional investments and advanced technologies.

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Кириллова О.В., Кириллова В.Ю. ІНТЕЛЕКТУАЛЬНІ ПОРТОВІ КЛАСТЕРИ ЯК СУЧАСНИЙ ІНСТРУМЕНТ РОЗВИТКУ ГЛОБАЛЬНОЇ СИСТЕМИ ТРАНСПОРТНИХ КОМУНІКАЦІЙ І СТРАТЕГІЧНИЙ ВЕКТОР ПІСЛЯВОЄННОГО ВІДНОВЛЕННЯ ПОРТОВОЇ ІНДУСТРІЇ УКРАЇНИ

Стаття досліджує Інтелектуальні Портові Кластери як сучасний інструмент розвитку глобальної транспортної системи та стратегічний вектор післявоєнного відновлення портової інфраструктури України. Метою роботи є обґрунтування стратегічної ролі Інтелектуальних Портових Кластерів у глобальній транспортній мережі, оцінка перспектив їх розвитку та інтеграції в портову інфраструктуру України з урахуванням сучасних технологічних тенденцій і викликів післявоєнного відновлення. Основна увага приділяється аналізу інноваційних технологій, таких як цифровізація, автоматизація та інтеграція цифрових платформ, що сприяють оптимізації портових операцій, підвищенню ефективності управління вантажопотоками та забезпеченню екологічної стійкості портів. Окремо розглянуто впровадження технологій штучного інтелекту (AI), великих даних (Big Data), Інтернету речей (IoT), блокчейну та цифрових двійників для інтеграції й оптимізації транспортних процесів у реальному часі. Проаналізовано світові тенденції розвитку Інтелектуальних Портових Кластерів, зокрема використання автономних суден, роботизованих перевантажувальних механізмів та автоматизованих диспетчерських систем. Представлено кейси провідних портів світу, таких як Роттердам, Сінгапур і Гамбург, які демонструють ефективність цифрових технологій у підвищенні конкурентоспроможності портових операцій. Стаття також акцентує увагу на потенціалі Інтелектуальних Портових Кластерів для післявоєнного відновлення української портової інфраструктури. Визначено, що впровадження сучасних цифрових технологій може значно прискорити відновлення портів, підвищити їх конкурентоспроможність на міжнародному рівні та сприяти залученню інвестицій. Викладено пропозиції щодо інтеграції українських портів у глобальні транспортні мережі через використання інтелектуальних кластерних моделей. Результати дослідження показують, що Інтелектуальні Портові Кластери здатні суттєво підвищити ефективність портових операцій, знижуючи операційні витрати, оптимізуючи вантажопотоки та зменшуючи екологічне навантаження. Новизна роботи полягає в дослідженні потенціалу таких кластерів для відновлення економіки України через їх інтеграцію в глобальні технологічні екосистеми. Таким чином, стаття підтверджує важливість Інтелектуальних Портових Кластерів як ключового інструменту модернізації транспортної інфраструктури, підвищення стійкості портів та інтеграції їх у світову транспортну екосистему. Запропоновані рекомендації можуть бути використані при розробці Національних стратегій розвитку портової галузі України в післявоєнний період. Дослідження є важливим внеском у розвиток Концепцій Розумних Портів (Smart Ports) та Інтелектуальних Портових Кластерів (Smart Port Clusters), а також у процес інтеграції новітніх технологій у транспортні системи. Результати роботи можуть бути використані для розробки Національної стратегії розвитку Розумних Портів та Інтелектуальних Портових Кластерів, яка передбачатиме законодавчі ініціативи, фінансування інвестиційних проєктів та розвиток міжнародних партнерств. Впровадження Інтелектуальних Портових Кластерів дозволить зменшити операційні витрати, підвищити продуктивність і знизити екологічні витрати, сприяючи розвитку економіки України, зокрема портового сектора.

***Ключові слова:** smart-порти, портові кластери, інтелектуальні портові кластери, smart port clusters, цифровізація портів, автоматизація портових операцій, штучний інтелект у портах, великі дані на транспорті, інтернет речей (iot) у портах, зелені технології у портах, стратегії розвитку портів, вантажні перевезення.*