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Smart Port Concept: A Case Study Of Port-Integrated Autonomous Networks

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ABSTRACT

The article explores the concept of a Port-Integrated Autonomous Network (PIAN) as a systemic model of the digital transformation of seaports in the context of innovative technologies. The PIAN combines autonomous port operations, distributed artificial intelligence, global blockchain document management, predictive analytics tools, and sustainable ecosystems. The article presents several mathematical models - phase implementation (PRM), stakeholder collaboration (SCM), and continuous innovation (CIM) - that allow optimization of efficiency, reduction of risks, and taking into account communication costs. The author identifies key technological components of smart ports, including autonomous equipment, digital platforms, sensor infrastructure, predictive maintenance, and intelligent traffic management systems. Special attention is paid to the legal aspects of implementation, particularly challenges in cybersecurity and regulatory compliance (GDPR, etc.). Based on the analytical model, a roadmap for the gradual introduction of technologies in ports with different readiness levels is proposed, allowing PIAN to be adapted to the specifics of local conditions. The article forms a theoretical and methodological basis for port administrations and logistics operators seeking to improve port infrastructure's efficiency, flexibility, and sustainability in the maritime industry's digital transformation context.

1. Introduction.

Smart ports are emerging as a revolutionary approach to maritime transportation management to meet the growing global trade efficiency, sustainability, and viability demands. Smart ports leverage digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics to optimize port operations, improve security, and reduce environmental impact. This shift is not just a technological modernization but a comprehensive transformation of how ports operate, in line with the global movement towards more intelligent, greener, and more integrated supply chains.

The development of smart ports is becoming increasingly important as global trade volumes continue to grow, requiring ports to efficiently handle more goods while minimizing their carbon footprint and operating costs. However, the transition to smart port operations is fraught with integration, security, and stakeholder coordination challenges, which this study aims to address by developing a comprehensive Port-Integrated Autonomous Network (PIAN). The primary objectives of this study are to create a multi-objective optimization model for smart port implementation, explore the potential benefits and challenges, and provide a roadmap for phased adoption of these technologies.

A growing volume of interdisciplinary research covering energy efficiency, resource management, digital transformation, and legal aspects accompanies the development of the smart port concept. Papers [1]-[8] describe the key principles of energy modernization of ports, including the introduction of re-

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newable energy sources, green infrastructure, and effective management. This creates the necessary basis for the sustainable functioning of port systems, which is critical in light of the PIAN concept. Further studies [9]-[13] systematize approaches to assessing the maturity of smart ports, highlighting key indicators of productivity, adaptability, and technological readiness. Papers [14]-[16] highlight the logistical challenges and potential of digital transformation in developing countries, including Ukraine, which allows the PIAN to be adapted to local conditions. An important role in shaping the global context is played by sources [17]-[21], which analyze the impact of digitalization on the structure of port management, the role of artificial intelligence, and the effectiveness of blockchain solutions.

Another important line of research is the issue of maritime safety, reliability, and environmental compliance. Works [22]-[26] analyze the implementation of technologies in terms of environmental protection, cyber threats, and social risks. Sources [27]-[29] focus on the operational sustainability of equipment and optimization of replacement periods, which is important for asset management in a highly automated environment. The safety dimension of maritime transportation, including maneuverability, the impact of risk factors, and the effectiveness of management decisions, is discussed in [30]-[33]. Support for the engineering reliability and technical compatibility of new solutions in the transport infrastructure is given in [34]-[36].

Models of adaptive management, data integration in logistics chains, and assessment of the operational efficiency of ship systems are studied in [37]-[40]. At the same time, regional cases of implementation of smart/green port concepts in [41]-[43] allow for the reflection of practical adaptation scenarios in different conditions. The review is completed by [44]-[47], which focuses on assessing environmental safety, forecasting the technical condition of ships, implementing energy-efficient positioning systems, and the impact of hydrometeorological factors on operational efficiency.

Thus, combining the analyzed sources forms a holistic theoretical and applied platform for developing and implementing the PIAN concept as a comprehensive model for digitally rethinking port infrastructure.

Despite the extensive research on smart ports, there is a noticeable gap in the literature regarding integrating distributed AI systems and blockchain technology in port operations. This study addresses these gaps by proposing a comprehensive, integrative model that leverages these technologies for enhanced efficiency and security.

2. Materails and Methods.

The embrace of digital thinking and the integration of innovative technologies provide ports with a significant competitive advantage. By modernizing operations, streamlining processes, and providing efficient services, ports can attract more shipping companies and strengthen their position in the maritime industry. As the industry evolves, embracing digital transformation is not just optional but essential to staying relevant in a changing landscape.

The maritime industry has significantly transformed, focusing on digital technologies in shipping and port operations. The shift from traditional methods to innovative solutions, such as the Internet of Things (IoT), cloud computing, mobile applications, and blockchain technology, is critical to managing increased cargo volumes and larger vessels. The use of these technologies increases the efficiency of port operations, exemplified by the role of IoT in managing vessel and cargo movements and the use of cloud services to analyze and coordinate data.

The creation of modern platforms that bring together maritime logistics stakeholders plays a central role in this digital evolution, facilitating better collaboration and coordination. These platforms optimize existing processes and open up new business opportunities, generating additional revenue streams. Digitalization plays a key role in the ongoing transformation of the maritime industry, enabling more efficient, coordinated, and connected port operations and promoting resilience and competitiveness in a rapidly changing global economy.

Today's maritime industry requires ports to digitally transform to remain competitive. Adopting digital approaches is necessary for several reasons (Table 1).

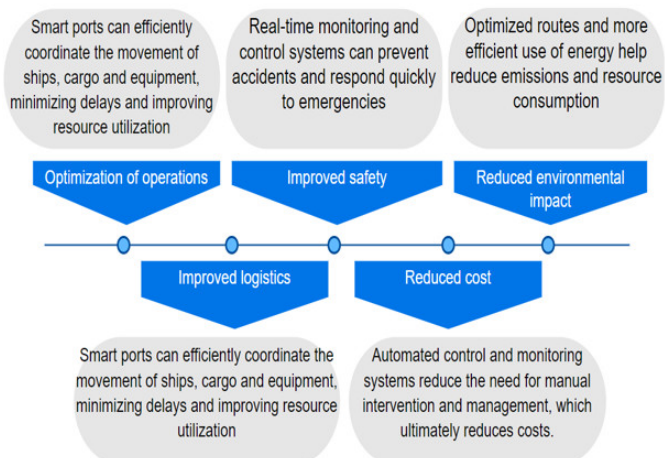
Table 1: Digital solutions in port operations.

Aspects	Description	Impact
Operational Efficiency	Digital tools streamline port activities by enhancing coordination among vessel traffic, cargo, and workforce.	Results in reduced waiting times, improved throughput, and a smoother flow of goods.
Accuracy and Transparency	Digital systems facilitate the collection and real-time analysis of vast data.	Enhances forecasting accuracy, improves resource planning, and boosts operational transparency.
Customer-Centric Approach	Digital technologies enable ports to offer enhanced services to customers.	Real-time tracking, automated alerts, and online data access increase customer satisfaction.
Adaptability	Ports need to adjust to the ever-changing global economic landscape.	Digital strategies enable quick responses to trade changes and flexible adaptation to new demands.
Cost Reduction	Automation and process optimization decrease resource, fuel, and time expenditures.	Leads to significant reductions in overall port operation costs.
Innovative Image	Ports adopting modern technologies are more appealing to shippers and consignees.	Attracts new customers and partners by projecting a forward-thinking image.
Competitive Advantage	Ports proficient in digital technologies gain a competitive edge over those using outdated methods.	Strengthens market position and draws in more cargo.

Source: Authors.

The digital transformation of ports not only enhances operational efficiency and adaptability but also positions them to effectively meet the demands of today's dynamic economic environment, ensuring long-term competitiveness. Seaports are critical to the global economy, facilitating the smooth exchange of goods and raw materials. However, the increasing volume of maritime cargo, along with heightened sustainability and security demands, necessitates innovations to optimize port operations and resource utilization. This has led to the rise of smart ports—seaports that leverage cutting-edge digital technologies and automation to streamline operations and improve management. These technologies include the Internet of Things (IoT), artificial intelligence (AI), data analytics, and automated control systems. The clear advantages of adopting smart port technologies are illustrated in the following diagram (Fig. 1).

Figure 1: Key benefits of smart port implementation.



Source: Authors.

Smart ports consist of several key components, including IoT infrastructure, which consists of sensors and devices installed in the port and on ships to collect data on the movement and status of equipment. Machine learning and artificial intelligence algorithms are used to collect and analyze the data to provide actionable insights. Automated systems minimize manual intervention and improve process efficiency, including robotics, unmanned vehicles, and cargo-handling systems. Digital platforms, such as virtual control and coordination systems, facilitate the seamless interaction of all port operations.

Examples of smart technology in seaports include autonomous cranes and vehicles that speed up cargo operations, smart containers with sensors to monitor their condition and location, and predictive maintenance tools that analyze data to predict equipment maintenance needs to reduce downtime.

However, smart ports also face challenges such as cybersecurity risks, system integration issues, and the need for specialized staff training on new technologies. Despite these challenges, the potential benefits of smart ports are enormous. They can increase efficiency and resilience in maritime freight transportation, ultimately contributing to a more streamlined and secure global trade system. These benefits and challenges of smart ports are summarized in Table 2.

Table 2: Challenges in implementing the smart port concept.

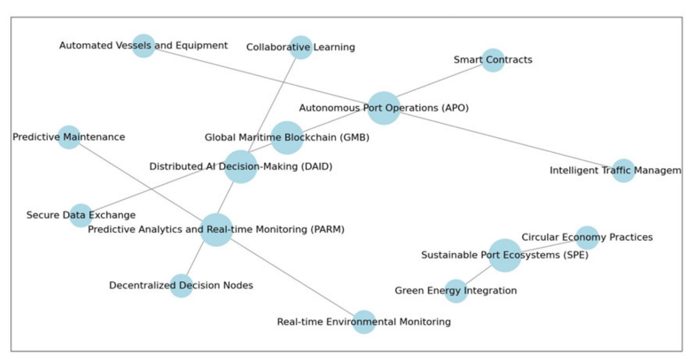
Challenge	Description
Cybersecurity	Smart ports are vulnerable to cyber threats due to interconnected systems. Protecting data and preventing unauthorized access is crucial.
System Integration	Integrating diverse systems and devices from different vendors into a unified digital platform poses complexity and requires standardized protocols.
Infrastructure Adaptation	Significant investment is needed to adapt physical port infrastructure to support new technologies and automated systems.
Data Management	Managing large volumes of data requires efficient systems for collection, storage, processing, and analysis, often relying on advanced AI tools.
Social and Workforce Impact	Automation may impact jobs and require workforce upskilling, necessitating careful management of social and economic implications.
Regulatory Compliance	Smart technologies must navigate complex legislative and regulatory environments, including data privacy and security norms.
Personnel Training	Training and retraining staff to handle new technologies and responsibilities can be challenging, especially for older employees.
Automation Balance	Balancing automation with manual processes is essential to maintain operational flexibility and adapt to changing conditions.
Compatibility with Vessels	Ensuring smart port systems are compatible with the technologies used on ships and by logistics companies is vital for smooth operations.
Environmental Considerations	Smart technology implementation should aim to reduce environmental impact, promoting sustainability in port operations.

Source: Authors.

3. Results and Discussion.

The Port-Integrated Autonomous Network (PIAN) concept is a forward-looking scheme aimed at revolutionizing port operations through the integration of autonomous systems, artificial intelligence-based decision-making and sustainable practices. PIAN is a holistic approach to port modernization, addressing key challenges and paving the way for a more efficient, safer and greener maritime industry.

Figure 2: Smart port key componets and interrelations.



Source: Authors.

With ports' ongoing digital transformation, the development and implementation of PIAN will be critical for ports seeking to remain competitive and adaptable in a rapidly changing economic landscape. This system optimizes current processes and opens up new opportunities for innovation, providing significant benefits to stakeholders across the maritime logistics chain.

1. Autonomous Port Operations (APO):

- Automated Vessels and Equipment: In today's smart ports, a significant advancement is the introduction of fully autonomous vessels and port equipment such as cranes and vehicles. These autonomous systems are designed to operate with minimal human intervention. Managed by sophisticated artificial intelligence control centers, these systems optimize various operational aspects including routing, docking and cargo handling processes. Artificial intelligence systems continuously analyze data from sensors and other sources, making real-time adjustments to improve efficiency and reduce errors.
- Intelligent Traffic Management: Smart Ports deploy artificial intelligence algorithms to predict and efficiently manage port traffic. These algorithms analyze huge amounts of data to predict the arrival and departure of ships, optimizing schedules to minimize congestion at the port. This not only reduces waiting time for ships, but also ensures a smoother and more efficient flow of goods. The system can dynamically adjust to changing conditions, such as weather or unexpected delays, to maintain optimal operations.

2. Distributed AI Decision-Making (DAID):
   - Decentralized decision nodes: Every port, terminal and vessel in a smart port network is equipped with artificial intelligence-based decision nodes. These nodes interact in real time with each other and with centralized control systems to provide decentralized decision-making. They analyze local data to make informed decisions about resource allocation, maintenance planning and emergency response without the need for centralized control. This decentralized approach enables faster response times and reduces the risk of bottlenecks in decision-making processes.
   - Collaborative learning: Artificial intelligence systems in smart ports are designed to share and learn from each other across the network. This collaborative learning approach allows the entire network to continuously improve and adapt to new challenges. As AI systems encounter different scenarios and challenges, they share solutions and optimizations across the network, resulting in improved system efficiency and resilience over time.
3. Sustainable Port Ecosystems (SPE):
   - Green energy integration: Smart ports are increasingly incorporating renewable energy sources such as solar, wind and wave energy into their operations. Artificial intelligence systems play a critical role in optimizing the consumption of these green energy sources, ensuring that the port's energy needs are met in a sustainable manner. This integration reduces the port's carbon footprint and contributes to broader environmental goals, aligning with global efforts to combat climate change.
   - Circular Economy Practices: Smart ports are adopting circular economy practices where waste and byproducts of port activities are recycled or reused. Resource management systems based on artificial intelligence ensure that waste is minimized and resources are used optimally. This not only reduces environmental impact, but also creates economic value from materials that would otherwise be discarded.
4. Global Maritime Blockchain (GMB):
   - Secure data exchange: The use of blockchain technology in smart ports increases the security and transparency of data transactions. A blockchain-based digital ledger records all transactions on the port network, ensuring that data is immutable and accessible only to authorized parties. This secure data exchange reduces the risk of information leakage and ensures the integrity of sensitive data such as bills of lading and customs documentation.
   - Smart contracts: Automated smart contracts on blockchain facilitate smooth and efficient transactions between shipping companies, port authorities and logistics providers. These contracts automatically fulfill agreed terms and conditions when certain conditions are met, reducing the need for manual paperwork and speeding up processing times. This automation simplifies port operations and reduces the likelihood of human error in contractual agreements.
5. Predictive Analytics and Real-time Monitoring (PARM):
   - Predictive maintenance: Sensors embedded in port equipment constantly monitor its condition and performance. Artificial intelligence algorithms analyze this data in real time to predict the need for maintenance before a breakdown occurs. By planning maintenance in advance, ports can avoid costly downtime and extend equipment life, leading to improved operational efficiency and lower operating costs.
   - Real-time environmental monitoring: Smart ports use artificial intelligence systems to monitor environmental factors such as air and water quality. These systems can adjust port operations in real time to minimize environmental impact, such as reducing emissions during periods of heavy pollution or adjusting waste management practices to prevent water pollution. This proactive approach to environmental management helps ports comply with environmental regulations and contribute to the achievement of sustainable development goals (Table 2).

Table 3: Key elements of smart ports concept.

Component	Description	Impact
Autonomous Port Operations (APO)	Automated systems for vessels and port equipment, managed by AI to optimize operations.	Reduces human intervention, optimizes routing, docking, and cargo handling, leading to increased efficiency.
Intelligent Traffic Management	AI algorithms for predicting and managing port traffic to minimize congestion.	Reduces waiting times, ensures smooth flow of goods, and improves overall port efficiency.
Distributed AI Decision-Making (DAID)	Decentralized decision nodes and collaborative AI systems for real-time, local decision-making.	Enhances decision-making speed, reduces bottlenecks, and increases the efficiency of resource allocation and emergency responses.
Collaborative Learning	AI systems share experiences across the network to continuously improve efficiency.	Ensures the entire network becomes more efficient and resilient over time, adapting to new challenges effectively.
Sustainable Port Ecosystems (SPE)	Integration of renewable energy and circular economy practices in port operations.	Reduces carbon footprint, optimizes resource use, and contributes to global sustainability goals.
Green Energy Integration	AI-driven optimization of renewable energy consumption within port operations.	Ensures sustainable energy use, reduces environmental impact, and supports energy efficiency initiatives.
Circular Economy Practices	Recycling and repurposing of waste materials generated by port operations.	Minimizes waste, creates economic value from byproducts, and aligns with sustainability efforts.
Global Maritime Blockchain (GMB)	Blockchain-based systems for secure and transparent data exchange within the port network.	Enhances data security, ensures transaction transparency, and prevents unauthorized access to sensitive information.
Secure Data Exchange	Blockchain ledger records all transactions, ensuring data integrity and security.	Prevents data breaches, maintains confidentiality, and ensures compliance with data security regulations.
Smart Contracts	Automated contracts that facilitate seamless transactions between stakeholders.	Reduces paperwork, speeds up processing times, and minimizes human error in contractual agreements.
Predictive Analytics and Real-time Monitoring (PARM)	AI-driven predictive maintenance and environmental monitoring to optimize operations and reduce impact.	Prevents equipment failures, reduces downtime, and ensures compliance with environmental regulations.
Predictive Maintenance	Real-time analysis of equipment health to schedule maintenance before failures occur.	Extends equipment lifespan, reduces operational costs, and improves the reliability of port operations.
Real-time Environmental Monitoring	AI systems monitor environmental factors and adjust port operations accordingly.	Minimizes environmental impact, ensures regulatory compliance, and supports sustainability initiatives.

Source: Authors.

To create an implementation algorithm for the proposed smart port system, we can develop a multi-objective optimization model that integrates various key performance indicators (*KPIs*) related to smart port operation.

This model can be used to manage phased implementation, stakeholder collaboration and continuous innovation processes:

1. Phased Rollout Model (PRM). The phased rollout can be modeled as a multi-stage decision-making process using dynamic programming. The objective is to maximize operational efficiency while minimizing risk during each phase:

$$\text{Maximize } Z = \sum_{t=1}^{T} (E(t) - R(t)), \quad (1)$$

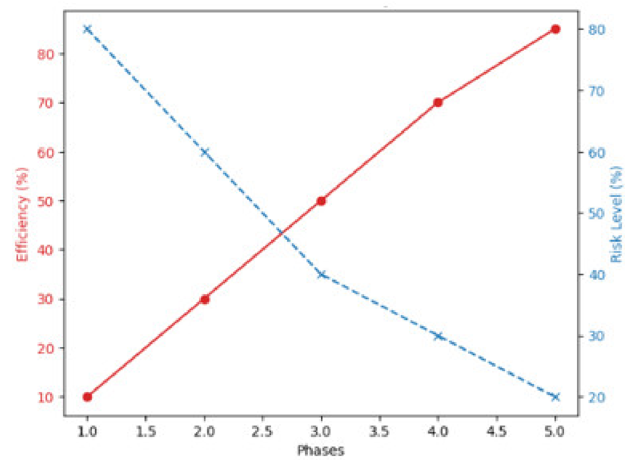
where: Z - the total net benefit over time T, $E(t)$ - the expected efficiency gain in phase t, $R(t)$ - the associated risk in phase t.

Constraints: $E(t) \geq E_{min}$, where E_{min} - the minimum acceptable efficiency gain, $R(t) \leq R_{max}$, where R_{max} - the maximum allowable risk.

The dynamic programming model used in this study calculates the optimal phase rollout by considering both the efficiency gains and associated risks. This approach allows for a flexible and adaptive implementation strategy that can respond to real-time data inputs.

Figure 3 shows a graph with the x-axis representing the phases of implementation and the y-axis representing the efficiency gains and the level of risk. The goal is to maintain a balance where the effectiveness consistently outweighs the risk, or in other words, the effectiveness increases and the risk decreases or remains manageable throughout the phased implementation.

Figure 3: Phased Rollout Efficiency vs. Risk Curve.



Source: Authors.

2. Stakeholder Collaboration Model (SCM). The collaboration can be modeled using a network graph, where nodes represent stakeholders, and edges represent communication channels, objective function:

$$\text{Minimize } C = \sum_{i=1}^{N} \sum_{j=1}^{M} d_{ij} \times t_{ij}, \quad (2)$$

where: C - the total communication cost, $d_{ij}$the distance or complexity of communication between stakeholder i and stakeholder j, t_{ij}- the time required for communication.

Constraints:

1. $t_{ij} \leq t_{max}$ for all i, j, where t_{max}- the maximum allowable communication time.
2. The network must be fully connected to ensure all stakeholders are engaged.

Figure 4 shows how communication and collaboration between stakeholders is structured and optimized. A network diagram showing nodes (stakeholders) and edges (communication channels). In some cases, the thickness of the channels may also reflect the frequency or intensity of communication.

3. Continuous Innovation Model (CIM). This can be modeled as an iterative process of innovation cycles, using evolutionary algorithms to continuously improve the system.

Objective Function:

$$\text{Maximize } I = \sum_{k=1}^{K} (G_k - C_k), \quad (3)$$

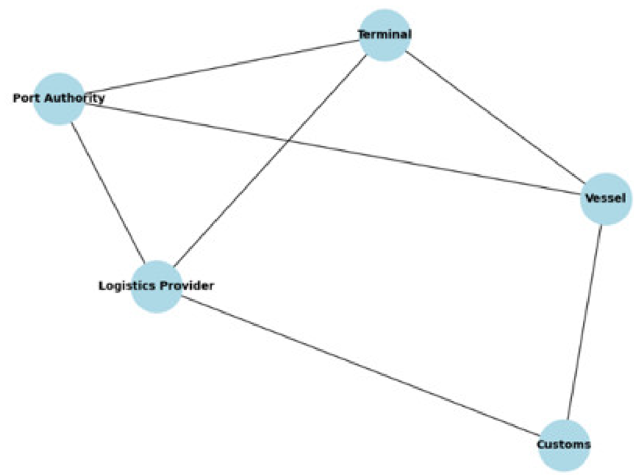
where: I - the total innovation gain, G_k- the gain from innovation in cycle k, C_k - the cost of innovation in cycle k.

Constraints:

1) $G_k \geq G_{min}$, where G_{min} - the minimum gain required to proceed to the next cycle;

2) $C \leq C_{max}$, where C_{max} - the budget constraint for each cycle.

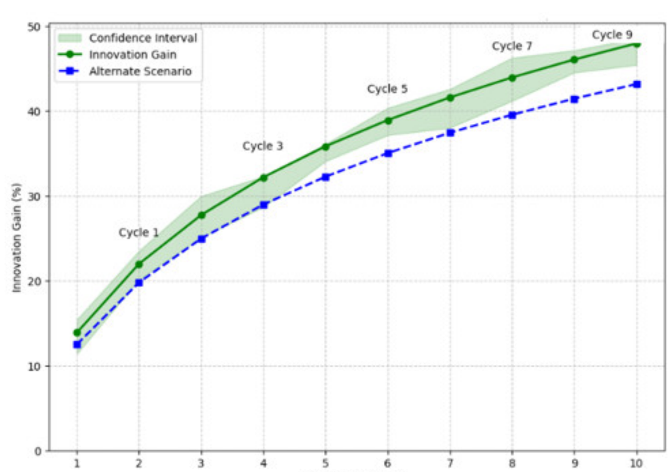
Figure 4: Stakeholder collaboration network.



Source: Authors.

The graph in Figure 5 models the iterative improvement of innovation gains over several cycles, which is important for understanding the dynamics of sustainable innovation in smart port development. The graph illustrates logarithmic growth, showing how innovation gains increase as cycles pass. The shaded confidence interval highlights the potential variability in results, while the alternative scenario offers a comparative perspective of different strategies and emphasizes the importance of continuous innovation to achieve significant improvements in smart port performance, considering both uncertainty and alternative approaches.

Figure 5: Continuous innovation curve: analysis of innovation dynamics.



Source: Authors.

The expressions below are intended to represent the mathematical foundations underlying the key components of a smart ports implementation strategy. Each equation corresponds to a specific aspect of the strategy, providing a theoretical framework for optimization and decision-making processes.

1. Dynamic programming for phased rollout models the optimization of phased rollout in smart ports:

$$Z_t = \max\{Z_{t-1} + E(t) - R(t)\}\, Z_t = \max\{Z_{t-1} + E(t) - R(t)\} \tag{4}$$

where Z_t- the cumulative efficiency at time t, $E(t)$ - the efficiency gain, and $R(t)$ - the risk. The goal is to maximize efficiency while minimizing risk over time.

2. Network Optimization for Stakeholder Collaboration models the optimization of collaboration among stakeholders in the port network.

$$\text{Minimize } C = \sum_{i=1}^{N}\sum_{j=1}^{M} d_{ij} \times t_{ij} \text{Minimize } C = \sum_{i=1}^{N}\sum_{j=1}^{M} d_{ij} \times t_{ij} \tag{5}$$

where: C - the total collaboration efficiency, with v_{ij} - the communication velocity between nodes i and j, d_{ij}- communication distance, and tij- the time taken for collaboration. The equation summarizes these factors across all nodes and links to optimize overall network performance.

3. Evolutionary Algorithm for Continuous Innovation. This equation models continuous innovation in smart ports using an evolutionary algorithm.

$$G_{k+1} = G_k + \alpha\left(\frac{\partial G}{\partial t}\right) G_{k+1} = G_k + \alpha\left(\frac{\partial G}{\partial t}\right) \tag{6}$$

where G_k- the innovation gain at iteration k, α - the learning rate, and $\partial G/\partial t$ - the gradient of the gain function over time. This equation allows for iterative improvement in innovation strategies, ensuring that smart ports continuously evolve and adapt to new challenges.

The proposed models could be validated through simulation testing and case studies in selected ports, refining the algorithms and adjusting the parameters to real-world conditions.

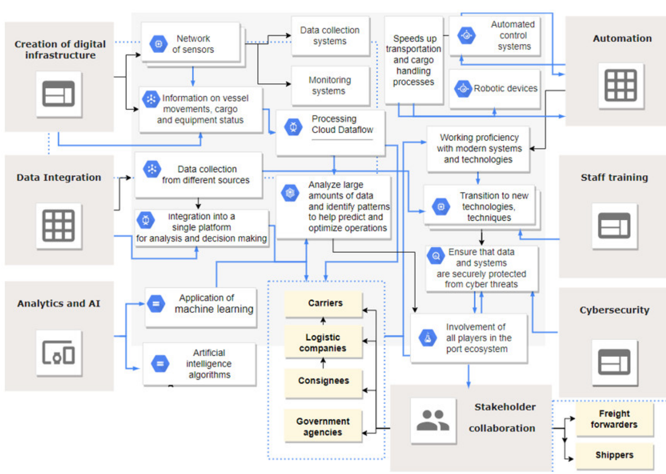
Implementing PIAN in large, complex ports can significantly reduce operating costs and environmental impact, making ports more attractive to global shippers. Unlike existing models that mainly focus on individual aspects of port operations, the PIAN system integrates multiple aspects, including autonomous operations and blockchain-based transactions, providing a more holistic approach to intelligent port management.

Smart ports embody the critical synergy of technology and human interaction needed to optimize operations and improve the customer experience. They offer integrated operations with real-time data exchange, predictive analytics and artificial intelligence, optimizing key areas such as traffic management and cargo handling. With a focus on sustainability, smart ports reduce waiting times and emissions by optimizing ship and truck movements and promoting environmentally friendly practices. Their adaptability is crucial in times of crisis, ensuring continuity of operations even in the face of labor shortages or remoteness. By integrating into wider supply chains, smart ports ensure seamless stakeholder coordination, minimizing disruption. Data-driven decision-making relies on comprehensive data analysis to optimize resource management and reduce downtime.

Despite these clear benefits, introducing innovative technologies requires careful investment and strategic long-term planning. Addressing legal and regulatory issues, such as data privacy and cybersecurity, is crucial to ensure responsible implementation. The agility of smart ports depends on their ability to adopt new technologies, and regular updates, ongoing training, and preparation for future innovations are key to maintaining their efficiency and effectiveness.

Smart ports are not just a modernization of traditional seaports but a transformational approach to cargo management. They combine advanced technology with traditional operations to create a more efficient, secure, and sustainable infrastructure for global trade. However, implementing smart ports requires a balanced strategy that takes into account technical and organizational factors. The key steps for implementing smart ports are described in Figure 6.

Figure 6: Integration of technology and organizational aspects in the process of implementing smart ports.



Source: Authors.

Legal aspects are also a critical aspect of smart port adoption, particularly in data privacy, cybersecurity, and regulatory compliance. As smart ports increasingly rely on interconnected systems and vast amounts of data, protecting sensitive information becomes paramount. Compliance with international and local data protection regulations, such as the General Data Protection Regulation (GDPR) in Europe, is necessary to avoid legal repercussions and maintain trust between stakeholders. In addition, cybersecurity measures must be robust to protect against potential cyber threats that could disrupt port operations or jeopardize critical infrastructure.

Dealing with this legal framework requires a proactive approach, constantly updating policies and procedures to keep pace with evolving regulatory standards and technological advances.

Smart ports must navigate a complex legal environment that imposes strict requirements for data processing and cybersecurity. Failure to comply with these regulations can result in significant legal and financial penalties. To mitigate these risks, port authorities must invest in robust cybersecurity measures and develop clear data management policies that comply with international standards.

While the PIAN framework shows great promise, further research is needed to explore its application in smaller ports and its adaptability to different regulatory environments. Future studies should also consider the long-term impacts of smart port technologies on employment and community relations.

Conclusions.

The concept of Port-Integrated Autonomous Network (PIAN) reflects a systematic approach to transforming seaports into a new generation of smart infrastructure. The integration of autonomous operations, distributed artificial intelligence, blockchain technologies, predictive analytics, and circular economy principles creates a new paradigm of port management that ensures increased efficiency, adaptability, and environmental sustainability. The proposed PRM, SCM, and CIM models demonstrate the possibility of phased implementation of innovations while minimizing risks and involving all participants in the logistics chain. The practical flexibility of PIAN allows it to be adapted to ports with different levels of digital maturity, taking into account local, legal, and technical features.

Particular attention should be paid to cybersecurity, legal regulation, and the development of digital competencies of staff, without which the innovation potential may be lost. PIAN is not only a technical solution, but a new management philosophy that changes the approach to port management in an unstable environment. Smart ports implemented according to this model optimize logistics processes, increase supply chain resilience, and create high-level digital integration. Further research should focus on testing the concept in small and medium-sized ports, which will facilitate its scaling in the broader maritime context of sustainable development.

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