Application of an IoT-Based Smart Port System to Improve Port Operational Management Efficiency in Indonesia

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Abstract

Indonesian ports play a vital role in supporting national and international logistics systems, as more than 90% of global trade volume is transported by sea. However, many Indonesian ports still face operational inefficiency, such as long vessel waiting times, high container dwelling times, and limited coordination among stakeholders. The implementation of a Smart Port System based on the Internet of Things (IoT) offers an innovative solution to support the digital transformation of ports toward the Port 4.0 era. This concept enables improvements in productivity, operational transparency, and energy efficiency through the integration of digital systems, data analytics, and process automation. This study is a systematic literature review examining international and national publications between 2019 and 2025 regarding Smart Port System implementation. The focus includes identifying key technologies (sensors, RFID, AGV, TOS), analyzing the impact on port performance indicators (throughput, dwelling time, crane productivity), and exploring barriers to implementation in the Indonesian context. The findings indicate that smart port adoption can significantly improve operational efficiency: throughput increases by 15–30%, dwelling time decreases by 25–40%, crane productivity rises by 20–35%, and energy consumption drops by 15–20%. However, the effectiveness depends on digital infrastructure readiness, investment, regulatory policy, and human resource capacity. This study recommends a phased implementation strategy starting with administrative digitalization, IoT deployment in key equipment, and full-scale data and cybersecurity integration. Such a framework is expected to strengthen Indonesia's port competitiveness and contribute to reducing national logistics costs.

Keywords: Smart Port, Internet of Things, operational efficiency, port, Port 4.*0*

INTRODUCTION

Ports serve as essential nodes in national and international logistics networks, facilitating maritime trade, cargo distribution, and regional economic connectivity. As one of the world's largest archipelagic countries, comprising more than 17,000 islands, Indonesia depends heavily on efficient port infrastructure to support domestic and international trade. Beyond their conventional function as gateways for maritime transportation, ports play a strategic role in stimulating regional economic development and strengthening national logistics integration. The original research data indicate that Indonesia's logistics costs account for approximately 23% of its Gross Domestic Product (GDP), substantially exceeding the estimated 8–12% observed in developed countries. These figures have been associated with discussions of national logistics performance, including the World Bank's Logistics Performance Index (LPI). One of the major challenges contributing to relatively high logistics costs is the limited efficiency of port operational management.

Conventional operational challenges, including prolonged vessel waiting times, excessive container dwelling times, manual administrative procedures, and insufficient data integration among port stakeholders, continue to affect port performance. These limitations may reduce cargo-handling productivity, increase operational costs, and weaken the competitiveness of Indonesian ports relative to major regional maritime hubs, including the Port of Singapore and Port Klang in Malaysia. Improving operational efficiency therefore requires a comprehensive approach that integrates technological innovation, institutional coordination, and data-driven management practices. The advancement of digital technologies and the emergence of Industry 4.0 have created significant opportunities to transform conventional port management into integrated Smart Port systems. Through the adoption of the Internet of Things (IoT), Big Data Analytics, and automation technologies, port operations can be monitored and coordinated in real time. These technologies enable continuous data collection, improved operational visibility, predictive decision-making, and systematic process optimization. Consequently, the development of Smart Port infrastructure represents a potential strategy for enhancing logistics efficiency and improving the reliability of maritime transportation services.

Several internationally recognized ports, including Rotterdam in the Netherlands, Hamburg in Germany, and Busan in South Korea, have implemented digital transformation initiatives to improve logistics coordination and operational performance. Their technological developments include IoT-based monitoring systems that facilitate connectivity among vessels, container-handling equipment, logistics vehicles, and centralized operational control facilities. Previous reports have

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associated such technological integration with improvements in crane productivity of up to 35% and reductions in vessel waiting times averaging 40%. These reported improvements illustrate the potential benefits of digitally integrated port operations, although actual performance outcomes depend on implementation conditions and the characteristics of individual ports. In Indonesia, major ports such as Tanjung Priok, Tanjung Perak, and Makassar New Port have progressively introduced digital services and selected automation technologies. These initiatives represent important steps toward the modernization of port operations. Nevertheless, the implementation of digital systems remains uneven, and full interoperability among operational platforms and institutional stakeholders has not been universally achieved. Major challenges include limitations in digital communication infrastructure, insufficient availability of maritime technology specialists, and substantial investment requirements for IoT hardware, data management platforms, and supporting technologies.

Addressing these challenges requires a systematic assessment of the technological, operational, institutional, and regulatory dimensions of Smart Port implementation. Such an assessment is particularly important in Indonesia, where ports differ considerably in infrastructure capacity, cargo-handling volume, financial resources, and technological readiness. A standardized implementation model may therefore be insufficient to accommodate the diverse operational characteristics of national ports. Accordingly, this study aims to analyze the potential contribution of IoT-based Smart Port systems to improving port operational management efficiency in Indonesia. Specifically, the study examines the principal technological components of Smart Port systems, identifies barriers and opportunities associated with their implementation, and develops policy and strategic recommendations for gradual technology adoption. The findings are expected to provide a conceptual and operational reference for policymakers, port authorities, and terminal operators seeking to strengthen maritime logistics competitiveness through sustainable digital transformation.

LITERATURE REVIEW AND THEORETICAL BACKGROUND

Smart Port and Port 4.0 Concepts

The Smart Port concept represents an evolution from conventional port digitalization toward comprehensive integration between physical infrastructure and digital information systems. Within the Port 4.0 framework, ports are no longer viewed solely as cargo loading and unloading facilities but also as intelligent logistics hubs supported by advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics, and automation systems. According to Behdani (2023), Port 4.0 emphasizes the capability of port systems to collect, process, and analyze operational data in real time to support both operational and strategic decision-making.

The development of Smart Ports is generally associated with four principal technological and operational pillars.

First, digital connectivity refers to the ability of equipment, operational platforms, and information systems to communicate through interconnected data networks. Reliable connectivity enables continuous information exchange among port facilities, terminal operators, shipping companies, and logistics service providers.

Second, operational automation involves the application of automated equipment and control technologies to improve cargo-handling efficiency and operational consistency. Examples include Automated Guided Vehicles (AGVs), Automated Stacking Cranes (ASCs), and remote-control systems that reduce dependence on manual operations in selected terminal activities.

Third, data analytics and artificial intelligence support the processing of operational information to identify patterns, predict congestion, optimize cargo-handling schedules, and improve resource allocation. These technologies enable port managers to make decisions based on continuously updated operational data rather than relying exclusively on historical records or manual assessments.

Fourth, environmental sustainability emphasizes the optimization of energy consumption and the reduction of carbon emissions through intelligent energy management systems. This dimension integrates environmental performance into port operational planning and supports the development of more sustainable maritime logistics systems.

Collectively, these four pillars provide a foundation for improving operational efficiency, enhancing logistics transparency, and supporting environmental sustainability in modern port management.

The Role of IoT in Smart Port Systems

The Internet of Things represents a fundamental technological component of Smart Port development. IoT enables physical objects, including containers, logistics vehicles, cranes, and environmental monitoring equipment, to exchange information through interconnected communication networks. These objects can be equipped with sensors and identification devices that continuously collect and transmit operational data to centralized control systems. According to Durlik et al. (2023), IoT applications in port environments can be classified into four primary domains.

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The first domain is asset and container monitoring, which involves the utilization of Radio Frequency Identification (RFID), positioning technologies, and location sensors to monitor container movements and asset positions in real time. Such systems improve cargo visibility and support more efficient asset tracking throughout terminal operations.

The second domain is cargo-handling equipment automation, including intelligent crane systems equipped with sensors capable of identifying container weights, positions, and handling conditions. These technologies facilitate more accurate equipment monitoring and may support automated or semi-automated cargo-handling activities.

The third domain is port traffic management, which employs cameras, sensors, and interconnected monitoring systems to evaluate traffic movements within port areas. Information obtained from these systems can support vehicle scheduling, traffic prioritization, congestion monitoring, and the coordination of logistics transportation activities.

The fourth domain is energy and environmental management, which involves monitoring electricity consumption, equipment energy demand, and environmental indicators. Through continuous measurement and analysis, port operators can identify opportunities to reduce unnecessary energy consumption and support green port development initiatives.

Integrating these four domains can establish a comprehensive port information environment in which operational activities are continuously recorded, monitored, and analyzed. Such integration facilitates greater visibility across port operations and provides a technological foundation for improving coordination and operational decision-making.

Port Operational Efficiency Indicators

Port operational efficiency can be evaluated using several Key Performance Indicators (KPIs) that describe cargo-handling performance, infrastructure utilization, and operational reliability. These indicators provide measurable references for assessing port performance and identifying opportunities for operational improvement.

The principal indicators include:

1. Container throughput (TEUs per year): The number of twenty-foot equivalent units handled by a port over a specified period, commonly expressed on an annual basis.
2. Container dwelling time (days): The average period during which containers remain within the port terminal before departing the terminal area.
3. Crane productivity (moves per crane-hour): The number of container-handling movements completed by an individual crane within one operating hour.
4. Berth Occupancy Ratio (BOR): An indicator describing the utilization of available berth capacity over a specified observation period.
5. Vessel turnaround time (hours): The total period required for a vessel to complete the relevant port service activities, measured in this study from berthing until departure.

According to Munim (2023), the implementation of IoT technologies and automated systems has been associated with potential increases in port throughput of approximately 15–30%, alongside reductions in container dwelling time of up to 40%. Such improvements may result from reduced manual processing errors, stronger operational coordination, and more effective scheduling and resource allocation. The effectiveness of these technological interventions can be assessed by comparing port performance indicators before and after digital system implementation. Nevertheless, the magnitude of operational improvements may vary according to infrastructure characteristics, terminal capacity, cargo volume, equipment availability, and the level of technological integration achieved.

Empirical Studies on Smart Port Implementation

Previous studies have examined the application of Smart Port technologies in various international maritime logistics environments. The literature generally highlights the potential contributions of digital integration, operational automation, and data analytics to improvements in port management efficiency. Heilig et al. (2021) reported that the implementation of IoT-based systems and predictive analytics at the Port of Hamburg was associated with a reduction in vessel waiting times of approximately 35%. The integration of digital information and operational monitoring systems was identified as an important component of improved coordination and resource utilization. Similarly, Lee and Lam (2022) discussed the implementation of logistics automation and real-time data integration at the Port of Busan, reporting an increase in container throughput of up to 25%. These findings suggest that digital technologies can support operational improvements when integrated with suitable terminal infrastructure and management practices.

Within the Indonesian context, Sari and Widodo (2024) examined digitalization initiatives at Tanjung Priok Port and Makassar New Port. Their study described the introduction of electronic documentation systems and digital berth reservation procedures as part of the modernization of port services. The findings indicated improvements in stakeholder coordination and reductions in administrative processing time, although the implementation had not yet generated substantial direct improvements in cargo throughput. These studies suggest that successful Smart Port implementation depends not only on the availability of advanced technological infrastructure but also on institutional readiness, regulatory support, organizational

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capacity, and the technical competence of port personnel. Consequently, technological modernization should be accompanied by effective governance and human resource development to ensure sustainable improvements in port performance.

Challenges of Smart Port Implementation in Indonesia

Despite the potential advantages of IoT-based Smart Port systems, their implementation in Indonesia faces several interconnected challenges involving technological infrastructure, investment capacity, human resources, regulatory frameworks, and workforce adaptation.

1. Digital Infrastructure Readiness

A significant challenge concerns the uneven availability of reliable digital communication infrastructure across Indonesian ports. While major commercial ports have progressively introduced digital management systems, many medium-sized and smaller ports continue to experience limitations in high-speed connectivity, network stability, and data center availability.

These conditions may restrict the implementation of IoT applications that require continuous data transmission and reliable communication between sensors, equipment, and operational control platforms. Improvements in network connectivity and data infrastructure are therefore essential prerequisites for broader Smart Port development.

2. Financial and Investment Constraints

The development of Smart Port infrastructure requires substantial financial investment in sensing equipment, communication technologies, automated cargo-handling systems, and digital operational platforms. Advanced technologies such as Automated Guided Vehicles (AGVs), intelligent monitoring systems, and Terminal Operating Systems (TOS) may involve significant acquisition, installation, integration, and maintenance costs.

For smaller port operators, limited financial resources may restrict their capacity to adopt these technologies independently. Consequently, government support, public–private partnerships, and phased investment strategies may be necessary to facilitate the implementation of digital port infrastructure.

3. Human Resource Capacity

Port digitalization requires personnel with technical competencies in data analytics, information technology management, cybersecurity, automated equipment operation, and digital system maintenance.

However, the availability of professionals with specialized maritime technology expertise remains an important consideration. Developing an adequately skilled workforce therefore requires systematic training, professional development, and institutional collaboration between port operators, educational institutions, and technology providers.

Strengthening human resource capacity is essential to ensure that digital technologies are operated effectively and integrated into existing port management practices.

4. Regulatory Frameworks and Data Interoperability

The implementation of integrated Smart Port systems also depends on the availability of compatible data standards, institutional coordination mechanisms, and appropriate regulatory frameworks.

Differences in data structures, operational platforms, and information exchange procedures may limit interoperability among port operators, shipping companies, logistics service providers, and government agencies. Without adequate system compatibility, digitalization initiatives may remain fragmented and fail to achieve comprehensive operational integration.

Cybersecurity and data protection are additional concerns because ports constitute critical infrastructure supporting national trade and transportation networks. Appropriate security policies, access controls, and system protection measures are therefore necessary to reduce the risks associated with interconnected digital operations.

5. Social and Employment Considerations

The adoption of automation technologies may alter labor requirements and operational responsibilities within port environments. Automated equipment and digitally integrated workflows can reduce the demand for certain manual activities while increasing the need for personnel with technical and analytical expertise. These changes may create employment-related challenges if workforce adaptation is not adequately planned. Accordingly, reskilling and upskilling programs are essential components of sustainable Smart Port implementation. Such programs can help existing port workers transition toward new operational roles, improve their technological competencies, and reduce the social impacts associated with increasing automation.

Overall, Smart Port development in Indonesia requires a coordinated strategy that addresses digital infrastructure readiness, financial accessibility, human resource development, regulatory integration, cybersecurity, and workforce sustainability. A phased implementation approach that reflects the operational characteristics and resource capacities of individual ports may provide a more practical pathway toward achieving long-term improvements in national port operational efficiency

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METHODS

Research Design and Approach

This study employed a systematic literature review (SLR) approach to identify, analyze, and synthesize findings from previous studies concerning the implementation of Internet of Things (IoT)-based Smart Port systems in port operations. This approach was selected because Smart Port development represents a multidisciplinary and rapidly evolving research field encompassing technological innovation, operational management, maritime logistics, and public policy. The systematic review was intended to provide a comprehensive understanding of the technological components, operational benefits, implementation challenges, and strategic considerations associated with Smart Port adoption. Particular attention was given to the potential contribution of IoT technologies to improving port operational management efficiency and their applicability within the Indonesian maritime logistics sector.

Data Sources and Literature Search

The study utilized secondary data obtained from scientific publications indexed in reputable international databases, including Scopus and Web of Science (WoS), as well as nationally accredited Indonesian journals classified under SINTA 1–3. The literature review covered publications released between 2019 and 2025 to capture recent developments in Smart Port technologies and digital transformation within the maritime industry. The principal literature sources included publications accessible through ScienceDirect, SpringerLink, Taylor & Francis, MDPI, and the Indonesian Maritime Transportation Journal (*Jurnal Transportasi Maritim Indonesia*).

The literature search employed keywords related to Smart Port technology and maritime operational efficiency, including *Smart Port*, *Internet of Things*, *Port 4.0*, *Maritime Logistics*, and *Digital Transformation in Ports*. These keywords were used to identify studies addressing technological applications, operational performance, and institutional aspects of port digitalization. The retrieved publications served as the basis for examining technological advancements, evaluating reported operational improvements, and identifying implementation challenges relevant to Smart Port development in Indonesia.

Stages of Data Analysis

The literature analysis was organized into four systematic stages to ensure that the findings addressed both technological and operational aspects of Smart Port implementation.

1. Identification of Key Smart Port Technologies

   The first stage involved identifying the principal technologies applied in IoT-based Smart Port systems. These technologies included interconnected sensors, Radio Frequency Identification (RFID), Automated Guided Vehicles (AGVs), Terminal Operating Systems (TOS), and intelligent energy management systems. The analysis focused on the operational functions of these technologies, particularly their roles in asset monitoring, cargo-handling automation, logistics coordination, operational data integration, and energy management.
2. Evaluation of Operational Impacts

   The second stage evaluated the operational impacts associated with Smart Port implementation by comparing port performance indicators reported before and after the adoption of digital technologies. The evaluation focused on changes in container throughput, container dwelling time, crane productivity, energy consumption, and berth utilization. These indicators were used to assess the potential contribution of IoT-based systems to operational efficiency and resource optimization.
3. Analysis of Implementation Barriers

   The third stage examined the barriers affecting Smart Port implementation, particularly within the Indonesian port sector. The analysis considered digital infrastructure readiness, financial and investment constraints, institutional and regulatory frameworks, and human resource capabilities. These factors were examined to identify challenges that may limit the adoption, integration, and long-term operation of Smart Port technologies.
4. Synthesis of Implementation Recommendations

   The fourth stage integrated the findings from the technological assessment, operational performance evaluation, and implementation barrier analysis. The synthesis was directed toward developing practical recommendations for the gradual implementation of IoT-based Smart Port systems in Indonesia. The proposed strategies considered differences in port infrastructure, operational capacity, technological readiness, and financial resources.

   The resulting recommendations were intended to provide a structured basis for supporting digital transformation initiatives and improving port operational management efficiency.

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Operational Efficiency Assessment Indicators

Five principal Key Performance Indicators (KPIs) were used to evaluate the reported operational impacts of Smart Port implementation. These indicators represent different dimensions of port performance, including cargo-handling capacity, operational time efficiency, equipment productivity, energy efficiency, and infrastructure utilization.

Table 1. Key performance indicators for assessing Smart Port operational efficiency.

No.	Performance indicator	Measurement unit
1	Container throughput	TEU/year
2	Container dwelling time	Days
3	Crane productivity	Moves/hour
4	Energy consumption per TEU	kWh/TEU
5	Berth Occupancy Ratio (BOR)	%

Container throughput was used to represent the volume of container traffic handled by a port during a specified period. Dwelling time indicated the duration containers remained within the terminal before departure, while crane productivity represented the efficiency of container-handling equipment. Energy consumption per TEU was considered an indicator of operational energy efficiency, enabling the assessment of energy requirements relative to container-handling activity. The Berth Occupancy Ratio was used to evaluate the level of berth utilization and provide information regarding the relationship between available berthing capacity and operational demand. Together, these indicators provided a quantitative framework for comparing operational performance reported in the selected literature.

Data Synthesis and Visualization

Quantitative findings extracted from the reviewed studies were organized and synthesized to compare operational performance before and after Smart Port technology implementation. The synthesis focused on identifying reported changes in the five selected efficiency indicators and examining their implications for port operational management. The results were presented through comparative tables and two principal types of graphical visualization: bar charts and radar charts. Bar charts were used to illustrate differences in selected operational performance indicators, while radar charts were intended to provide a multidimensional comparison of port efficiency characteristics. The combined presentation of quantitative indicators and descriptive findings was used to support the interpretation of operational efficiency trends and identify potential benefits and implementation challenges associated with IoT-based Smart Port systems. The resulting synthesis provided the analytical basis for developing recommendations concerning the phased adoption of Smart Port technologies in Indonesia.

RESULTS AND DISCUSSION

Impact of Smart Port Implementation on Operational Performance

The synthesis of 12 principal studies indicates that the implementation of IoT-based Smart Port systems has a significant impact on port operational efficiency. Table 1 summarizes the reported effects of Smart Port implementation on key operational performance indicators.

Table 1. Impact of Smart Port implementation on port operational performance.

Performance Indicator	Before Implementation (Average)	After Smart Port Implementation (Average)	Change (%)	Source
Throughput (TEU/year)	1,000,000	1,150,000–1,300,000	+15–30%	Munim (2023); Lee & Lam (2022)
Dwelling Time (days)	4.5–5.0	2.5–3.5	–25–40%	Sari & Widodo (2024); Nguyen et al. (2023)
Crane Productivity (moves/hour)	20–25	25–34	+20–35%	Heilig et al. (2021); Putra et al. (2023)
Energy Consumption (per TEU)	100% baseline	80–85%	–15–20%	Dagistan et al. (2025)
Berth Occupancy Ratio (BOR) (%)	70–80	60–65	–10–15%	Behdani (2023)

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Table 1 indicates that the most substantial efficiency gains were reported in the reduction of container dwelling time and the increase in crane productivity. These two indicators are directly associated with the implementation of automation systems and real-time data integration. The reported throughput increase of 15–30% also suggests that Smart Port technologies can improve cargo-handling capacity without necessarily requiring immediate physical port expansion. In addition, reductions in energy consumption and berth occupancy ratio indicate that Smart Port implementation may contribute not only to productivity gains but also to more efficient resource utilization.

Overall, the synthesized findings suggest that Smart Port systems create operational improvements by reducing delays, improving coordination, enhancing equipment utilization, and increasing the visibility of cargo-handling processes. However, the magnitude of these improvements varies across studies depending on port size, infrastructure readiness, degree of digital integration, and the specific technologies adopted.

Visual Analysis: Bar Chart

The bar chart illustrates the percentage changes observed in each key performance indicator following Smart Port implementation. This visualization highlights that the increase in throughput and crane productivity represents a major contribution to operational efficiency, while the reduction in energy consumption reflects an important sustainability-related benefit.

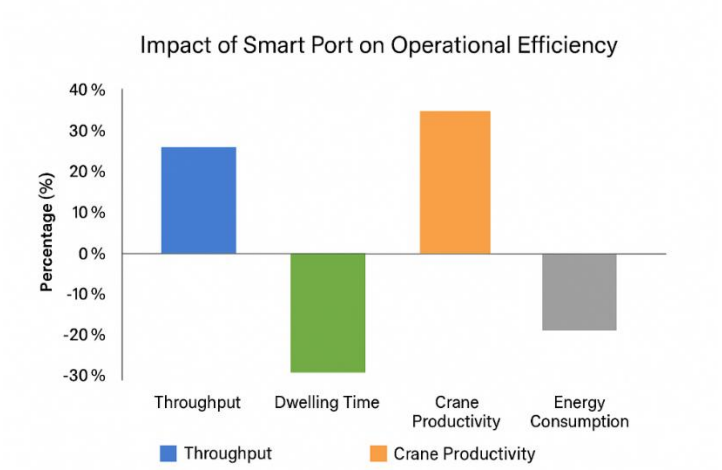


Figure 1. Bar chart of changes in operational efficiency after Smart Port implementation.

The visual comparison further emphasizes that Smart Port systems generate multidimensional improvements. Indicators associated with time efficiency and equipment productivity show the strongest operational gains, whereas energy efficiency and berth utilization demonstrate additional benefits related to infrastructure optimization and sustainable port operations.

Factors Influencing Implementation Success

Based on the reviewed literature, the success of Smart Port implementation depends on four principal factors.

1. Digital Infrastructure Readiness

Ports equipped with fiber-optic networks and reliable data center systems tend to achieve efficiency improvements more rapidly than ports with limited connectivity. Stable communication infrastructure is essential for supporting continuous sensor data transmission, real-time monitoring, and integrated operational control.

2. Human Resource Capacity and Digital Literacy

Technical training for port operators and technicians in the use of IoT-based systems has been shown to improve data reliability and reduce operational errors. This finding indicates that technological modernization must be accompanied by human resource development to ensure effective adoption and operation of Smart Port systems.

3. Regulatory and Government Policy Support

Policies such as the *National Port Community System* (NPCS) and the digitalization of port documentation support interoperability among port stakeholders and improve coordination between operators, regulators, and logistics service providers. Regulatory support is therefore a key enabling factor in the broader adoption of Smart Port technology.

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4. Investment and Public–Private Partnership (PPP) Schemes

The implementation of IoT technologies, smart cranes, and other advanced digital systems requires substantial financial investment. Public–private partnerships provide an effective mechanism for financing port modernization, particularly for ports facing budgetary constraints or high capital investment barriers.

Taken together, these four factors indicate that Smart Port implementation is not determined solely by technology availability. Instead, successful digital transformation depends on the interaction between infrastructure, human resources, governance, and financing arrangements.

Implications for Environmental Sustainability

In addition to economic and operational efficiency, Smart Port implementation also provides environmental benefits.

First, reduced vehicle idle time can lower CO_2 emissions by up to 15%. This reduction is associated with more efficient traffic management and shorter waiting times within port areas.

Second, the use of smart lighting systems and energy monitoring technologies contributes to lower electricity consumption at berths and terminal facilities. Such systems allow operators to monitor energy usage continuously and optimize electricity demand more effectively.

Third, the digitalization of administrative documents reduces paper consumption and decreases transport-related activities associated with manual document handling. This contributes to more environmentally sustainable administrative processes.

These findings indicate that the Smart Port concept is aligned with the objectives of Sustainable Development Goal (SDG) 9, concerning Industry, Innovation, and Infrastructure, and SDG 13, concerning Climate Action. Consequently, Smart Port development can be understood not only as a strategy for enhancing logistics performance but also as a mechanism for supporting greener and more sustainable port operations.

Relevant Case Studies in Indonesia

1. Tanjung Priok Port

Tanjung Priok Port has implemented *Inaportnet* and the *Electronic Berthing Request System* (e-BR). These systems reduced administrative processing time from an average of 6 hours to 2 hours. This improvement demonstrates the potential of digital systems to enhance procedural efficiency and reduce administrative delays.

However, data integration among institutions remains limited, which means that the resulting throughput improvement has not yet reached its full potential. This suggests that digitalization at Tanjung Priok has produced measurable benefits but still requires stronger system interoperability and broader institutional integration.

2. Makassar New Port

Makassar New Port has adopted a *Terminal Operating System* (TOS) and gate automation. The use of gate sensors and vehicle tracking improved traffic flow and reduced truck queues by up to 40%.

This case demonstrates that targeted digital interventions in traffic and terminal management can generate immediate operational benefits. It also indicates that even partial digital transformation can improve the efficiency of port access and cargo movement.

Together, these two case studies suggest that digital transformation in Indonesian ports is still at an early stage but has already produced positive and tangible results. They also show that the operational benefits of Smart Port systems can be realized incrementally through phased implementation.

Economic and Social Analysis

The implementation of Smart Port systems also generates economic and social impacts. From an economic perspective, reductions in loading and unloading time increase throughput capacity without requiring immediate physical expansion of berth infrastructure. This implies that digital transformation may improve port productivity while optimizing existing assets.

From a social perspective, Smart Port implementation changes labor demand by shifting the workforce requirement from manual labor toward technology-oriented operational roles. This transition may create challenges for workers whose tasks are replaced or transformed by automated systems. To maintain social balance and workforce competitiveness, upskilling and reskilling programs are required so that local labor can adapt to the needs of digitalized maritime operations. Therefore, Smart Port development should be accompanied by labor transition strategies that ensure the benefits of technological modernization are distributed more broadly and sustainably.

Overall, the findings indicate that IoT-based Smart Port implementation has the potential to improve port efficiency, support environmental sustainability, and reshape the economic and social dimensions of port operations in Indonesia. The success of this transformation, however, depends on coordinated implementation strategies that integrate infrastructure, investment, regulation, and workforce development.

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LIMITATIONS OF THE STUDY

This study has several limitations that should be considered when interpreting its findings. First, the research relies primarily on secondary data obtained from scientific publications and official reports. Consequently, the findings are predominantly conceptual and descriptive, reflecting the synthesis of previously reported evidence rather than direct empirical measurements. Primary field data remain limited, particularly for medium-sized and small ports in Indonesia that have not yet achieved comprehensive digitalization. This limitation restricts the extent to which the findings can represent the operational characteristics and technological readiness of different port categories across the country.

Second, a substantial proportion of the reviewed evidence originates from international case studies involving technologically advanced ports, including Rotterdam, Busan, and Hamburg. These ports generally possess more developed digital infrastructure, greater investment capacity, and more integrated operational management systems than many Indonesian ports. Therefore, the reported improvements in operational efficiency should be interpreted as indicative estimates rather than directly transferable performance outcomes. Additional field-based investigations in Indonesian ports are necessary to determine whether comparable improvements can be achieved under different infrastructure, institutional, and operational conditions.

Third, the study provides a limited assessment of the macroeconomic implications of Smart Port implementation, particularly its potential contribution to reducing national logistics costs. This limitation arises from the lack of consistent and integrated data across relevant institutions. Differences in data collection methods, reporting systems, and information accessibility among government ministries, port operators, and logistics service providers continue to present challenges for comprehensive economic analysis. As a result, the study cannot establish a direct quantitative relationship between Smart Port adoption and changes in Indonesia's overall logistics costs.

Finally, cybersecurity issues were not examined in sufficient depth, despite the increasing importance of protecting digitally interconnected port infrastructure against cyber threats. The extensive integration of sensors, operational technology, communication networks, and centralized information systems may introduce vulnerabilities that affect operational continuity and data security. Future research should therefore incorporate comprehensive cybersecurity assessments, including risk identification, system vulnerability analysis, data protection mechanisms, and operational resilience strategies for IoT-based Smart Port environments.

Overall, these limitations indicate that the findings should be interpreted within the scope of a secondary-data-based systematic literature review. Although the study identifies potential operational benefits and strategic implementation priorities, further empirical validation is required to establish their applicability and effectiveness across different Indonesian port environments.

POLICY AND IMPLEMENTATION RECOMMENDATIONS

The implementation of IoT-based Smart Port systems in Indonesia requires a comprehensive, integrated, and phased policy approach. Based on the findings of this review, strategic recommendations can be organized into three principal levels: national policy development, technical implementation at the port level, and human resource capacity development. These recommendations are intended to support the gradual transformation of conventional port operations into digitally connected, efficient, and sustainable maritime logistics systems.

National Policy Level

1. Development of a National Port 4.0 Roadmap

The Indonesian government should establish a comprehensive National Smart Port Roadmap to provide strategic guidance for digital transformation across the country's port network. The roadmap should define digitalization targets, system integration priorities, implementation stages, and measurable performance indicators. A national framework would help coordinate technological development among ports with different operational capacities and infrastructure characteristics. It would also provide a basis for monitoring implementation progress and evaluating the contribution of Smart Port technologies to national maritime logistics performance.

2. Integration of National Port Data Systems

The development or strengthening of an integrated digital platform, such as a National Port Community System (NPCS), is essential for improving information exchange among port stakeholders. Such a system should facilitate interoperability among shipping information, cargo documentation, logistics operations, customs procedures, and relevant government services. Effective data integration would reduce information fragmentation, improve operational transparency, and support more coordinated decision-making across the maritime logistics chain. The platform should be developed with consideration

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for existing national digital systems to avoid unnecessary duplication and ensure compatibility with established port management infrastructure.

3. Fiscal Incentives and Technology Investment

Fiscal incentives and innovative financing mechanisms should be considered to encourage port operators to invest in IoT infrastructure, operational automation, and digital management platforms. Potential measures include tax incentives, investment support, and Public–Private Partnership (PPP) arrangements. Such financing mechanisms are particularly relevant for medium-sized and smaller ports with limited capital resources. A phased investment strategy could enable operators to prioritize essential digital infrastructure before adopting more advanced automation technologies.

4. Data Standardization and Regulatory Development

The government should establish standardized data exchange protocols and information security requirements to support interoperability among port operators, logistics service providers, shipping companies, and regulatory agencies. Standardized digital communication frameworks would facilitate the integration of heterogeneous information systems and reduce technical barriers to data exchange. In addition, regulatory provisions addressing cybersecurity, data governance, system reliability, and information protection are necessary to safeguard critical port infrastructure and maintain operational continuity.

Technical Implementation at the Port Level

1. Digitalization of Administrative Services

The initial stage of Smart Port implementation should prioritize the digitalization of administrative processes, including electronic port documentation, electronic manifests, and vessel berth reservation systems.

Digital administrative services can reduce manual processing requirements, improve document traceability, and facilitate information exchange among relevant stakeholders. These systems also provide an essential foundation for the subsequent integration of operational data and more advanced Smart Port technologies.

2. Integration of IoT Devices and Asset Monitoring Systems

Port operators should progressively introduce IoT-based monitoring technologies for critical operational assets, including cargo-handling equipment, logistics vehicles, and containers. Technologies such as Radio Frequency Identification (RFID), Global Positioning System (GPS) devices, and load sensors can support real-time monitoring of asset locations, equipment utilization, and cargo-handling activities. The resulting operational data may improve asset visibility, reduce tracking errors, and support more effective resource allocation. Implementation priorities should be determined according to the operational requirements, infrastructure readiness, and financial capacity of individual ports.

3. Development of Intelligent Terminal Operating Systems

The integration of Terminal Operating Systems (TOS) with predictive analytics can improve cargo-handling planning, equipment allocation, and terminal scheduling. By processing real-time operational data, intelligent TOS platforms can support the identification of potential congestion, anticipate equipment requirements, and recommend operational adjustments. These capabilities may contribute to reduced waiting times, improved cargo-handling productivity, and more coordinated terminal operations. The effectiveness of intelligent TOS implementation depends on reliable data availability, appropriate system integration, and the ability of port personnel to interpret and apply analytical outputs.

4. Implementation of Energy Management Systems

IoT-based Energy Management Systems (EMS) should be considered to monitor and optimize energy consumption throughout port terminals. Such systems can integrate electricity meters, equipment monitoring devices, and automated control technologies to identify inefficient energy usage and support more effective energy management. The implementation of EMS can also contribute to Green Port initiatives by supporting energy conservation, reducing unnecessary electricity consumption, and improving environmental performance monitoring.

Human Resource Capacity Development

1. Maritime Digital Competency Training and Certification

Technical universities, maritime education institutions, and vocational training centers should develop curricula and professional certification programs addressing maritime digitalization, port IoT systems, data analytics, and cybersecurity. These initiatives would help prepare a workforce capable of operating, maintaining, and managing technologically advanced port systems. Collaboration between educational institutions and port operators is also important to ensure that training programs reflect actual industrial requirements.

2. Workforce Reskilling and Upskilling Programs

The transition toward automated port operations requires systematic workforce development strategies to support employees whose existing responsibilities may be affected by technological change. Reskilling and upskilling programs should provide opportunities for port workers to acquire competencies in digital equipment operation, system monitoring,

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maintenance, and technology-supported logistics management. Such programs would help maintain workforce adaptability, reduce employment-related disruptions, and support a socially sustainable transition toward Smart Port operations.

3. Collaboration with Technology Industries

Partnerships between port operators, government institutions, universities, and domestic and international technology companies should be strengthened to accelerate knowledge transfer and technological adoption. Industry collaboration can facilitate access to technological expertise, technical training, system development experience, and advanced digital solutions relevant to maritime logistics. In addition, collaboration with local technology providers may support the development of cost-effective systems adapted to the operational conditions of Indonesian ports, thereby reducing long-term dependence on external technology suppliers.

Overall, successful IoT-based Smart Port implementation in Indonesia requires coordinated efforts across government institutions, port operators, educational organizations, and technology providers. An integrated strategy combining national policy development, phased technological investment, operational system integration, and human resource capacity building can provide a practical foundation for improving port efficiency and supporting sustainable maritime logistics transformation.

CONCLUSION

This study highlights the strategic importance of implementing Internet of Things (IoT)-based Smart Port systems to improve port operational management efficiency in Indonesia. Based on the synthesis of previous studies, Smart Port technologies demonstrate considerable potential to enhance operational performance through digital connectivity, automation, real-time monitoring, and data-driven decision-making. The reviewed literature reports potential improvements in container throughput of approximately 15–30%, reductions in container dwelling time of 25–40%, increases in crane productivity of 20–35%, and reductions in energy consumption of 15–20%. These findings indicate that the integration of IoT and intelligent operational systems can contribute to more efficient cargo handling, improved resource utilization, and reduced operational delays. However, the reported performance improvements represent findings from the reviewed literature and should not be interpreted as universally achievable outcomes across Indonesian ports without further empirical validation.

Beyond operational and economic efficiency, Smart Port implementation offers potential environmental benefits through reduced energy consumption, lower emissions, and more efficient utilization of port infrastructure. The successful transformation of conventional ports into intelligent maritime logistics hubs depends primarily on digital infrastructure readiness, human resource capacity, and adaptive regulatory and policy support. Accordingly, a phased implementation strategy, beginning with administrative digitalization and progressing toward IoT-based asset monitoring, integrated operational systems, advanced data analytics, and comprehensive cybersecurity measures, provides a practical pathway for Indonesia's port modernization. By aligning technological investment with institutional readiness and workforce development, Indonesia has the opportunity to establish a more efficient, transparent, resilient, and environmentally sustainable national port system.

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