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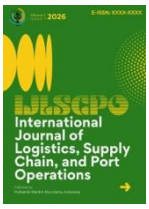

Digital Twin Technology and Smart Port Operations (Insights from Port Digitalization in Busan)

Aep Saepudin
Akademi Sekretari dan Manajemen Insulindo
E-mail: aepsaepudin150278@gmail.com id No. HP yg dpt dihubungi -

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Abstract: The rapid development of digital technologies has accelerated the transformation of port logistics systems worldwide. Ports are increasingly adopting advanced digital solutions to improve operational efficiency, enhance logistics coordination, and support the development of smart port ecosystems. One of the emerging technologies driving this transformation is digital twin technology, which enables the creation of virtual representations of physical port infrastructure and logistics operations using real-time data. This study aims to explore the role of digital twin technology in supporting smart port operations through the context of port digitalization at the Port of Busan. The study adopts a case study approach to examine how digital twin systems are implemented in port logistics environments and how stakeholders perceive their impact on operational management. Data were collected through semi-structured interviews with key stakeholders involved in port operations, supported by document analysis of port digitalization initiatives and industry reports. The findings reveal that digital twin technology enhances port operational efficiency by enabling real-time monitoring, predictive simulation, and data-driven decision-making in port management. The study also highlights the role of digital twin platforms in improving resource allocation and strengthening collaboration among port stakeholders. However, the implementation of digital twin systems presents challenges related to technological integration, infrastructure investment, and workforce capability development. This research contributes to the growing literature on smart port development and provides insights for port authorities and logistics managers seeking to implement digital twin technologies in port logistics systems.

Keywords: Digital Twin Technology, Smart Port, Port Logistics, Port Digitalization, Maritime Supply Chain

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INTRODUCTION

The rapid development of digital technologies has significantly transformed the global logistics and maritime industries. Ports, as critical nodes in international supply chains, are increasingly adopting advanced digital technologies to improve operational efficiency, enhance cargo handling processes, and strengthen supply chain coordination. As global trade continues to expand, port authorities are under increasing pressure to modernize logistics infrastructure and adopt innovative technologies that support smarter and more efficient port operations (Notteboom & Rodrigue, 2020).

One of the emerging technologies driving digital transformation in port logistics is digital twin technology. A digital twin refers to a virtual representation of physical systems that uses real-time data to simulate, monitor, and optimize operational processes. In the context of port logistics, digital twin systems allow port authorities to create digital models of port infrastructure, vessel movements, cargo handling operations, and logistics networks. These virtual models enable port managers to monitor operational activities in real time and simulate potential operational scenarios (Ivanov & Dolgui, 2021).

Digital twin technology provides several advantages for port logistics management. By integrating real-time data from sensors, logistics platforms, and operational monitoring systems, digital twins enable more accurate operational planning and predictive decision-making. Port managers can use these systems to anticipate congestion, optimize cargo flows, and improve resource allocation within port terminals. As a result, digital twin systems contribute to more efficient and resilient port logistics operations.

In addition to improving operational efficiency, digital twin technology also supports the development of smart ports. Smart ports utilize digital technologies, data analytics, and automated systems to enhance the management of port infrastructure and logistics activities. Through the use of digital twins, port authorities can integrate various operational data sources and create intelligent systems that support proactive logistics management and predictive maintenance of port equipment (Heilig, Schwarze, & Voß, 2017).

Among global ports, the Port of Busan has emerged as one of the leading examples of smart port development and digital transformation in maritime logistics. As one of the largest container ports in the world, Busan plays a strategic role in global trade and logistics networks. The port has invested significantly in digital technologies, including data platforms, automation systems, and digital twin initiatives aimed at improving the efficiency and reliability of port operations.

Despite the growing interest in digital twin technology within port logistics systems, the implementation of such technologies remains complex. Integrating digital twin systems into existing port infrastructure requires significant technological investment, advanced data integration capabilities, and strong collaboration among port stakeholders. In addition, port organizations must develop new operational strategies and technical skills to effectively utilize digital twin technologies.

Previous studies on port digitalization have largely focused on technological capabilities and performance outcomes of digital systems. However, there remains limited research exploring how stakeholders within port logistics ecosystems perceive and manage the adoption of digital twin technologies in practice. Understanding these perspectives is important for identifying the opportunities and challenges associated with digital twin implementation in smart port environments.

Therefore, this study aims to explore the role of digital twin technology in supporting smart port operations through the context of port digitalization at the Port of Busan. By examining how digital twin systems are integrated into port logistics operations and how stakeholders interact with these digital platforms, this research seeks to provide deeper insights into the transformation of port logistics systems through emerging digital technologies.

METHOD

This study adopts a qualitative research approach to explore the implementation of digital twin technology and its role in supporting smart port operations at the Port of Busan. A qualitative approach was selected because it enables a deeper understanding of how digital twin systems are implemented in port logistics environments and how various stakeholders perceive the adoption of advanced digital technologies in port management.

The research uses a case study design focusing on the Port of Busan, one of the largest container ports in the world and a leading example of smart port development in Asia. The case study approach allows the researcher to examine complex technological and operational processes within real-world port logistics environments. The Port of Busan was selected due to its active investment in digital technologies, including automation systems, data platforms, and digital twin initiatives aimed at improving port operational performance.

Data were collected through several qualitative data collection methods. First, semi-structured interviews were conducted with key stakeholders involved in port logistics and digital innovation initiatives. These informants included port authority officials, terminal operators, logistics managers, maritime technology specialists, and shipping company representatives who are directly involved in port operations. Purposive sampling was used to select participants who possess relevant knowledge and experience related to digital transformation and smart port development.

Second, document analysis was conducted to review official reports, port development strategies, technology implementation reports, and industry publications related to digital twin technology and port digitalization initiatives. These documents provided valuable insights into the strategic objectives, technological frameworks, and operational developments associated with smart port initiatives at the Port of Busan.

In addition, secondary data from maritime logistics studies and global port digitalization reports were analyzed to provide contextual understanding of digital transformation trends in port operations. These

secondary sources supported the interpretation of findings and provided broader perspectives on the role of digital twin technology in modern port logistics systems.

The collected data were analyzed using thematic analysis. This analytical process involved organizing interview transcripts and documents, coding key themes, and identifying patterns related to the implementation of digital twin technology in port logistics operations. Thematic analysis enabled the researcher to identify the operational benefits, strategic opportunities, and implementation challenges associated with digital twin systems in smart port environments.

To ensure the credibility and reliability of the research findings, data triangulation was applied by comparing information obtained from interviews, document analysis, and secondary sources. This triangulation process helped strengthen the validity of the findings and provided a comprehensive understanding of how digital twin technology supports smart port development and logistics optimization at the Port of Busan..

RESULTS AND DISCUSSION

The findings of this study reveal several important insights regarding the implementation of digital twin technology in supporting smart port operations at the Port of Busan. Based on interview data, document analysis, and industry reports, several key themes emerged that explain how digital twin systems contribute to improving port logistics management and operational decision-making.

Digital Twin for Real-Time Operational Monitoring

One of the main findings of this study is the ability of digital twin technology to provide real-time monitoring of port operations. Digital twin technology refers to the development of virtual models that replicate physical systems through the integration of real-time operational data, advanced analytics, and simulation technologies. In the context of maritime logistics, digital twins allow port authorities to create dynamic digital representations of port infrastructure, vessel movements, and logistics processes, enabling more effective monitoring and management of port operations (Tao, Zhang, Liu, & Nee, 2019).

The Port of Busan has implemented advanced digital platforms that collect operational data from multiple port systems, including vessel traffic monitoring systems, container terminal operations, and logistics information platforms. These diverse data sources are integrated into digital twin models that replicate the physical environment of the port in a virtual system. Through this integration, port authorities can obtain a comprehensive and real-time view of port activities, which improves situational awareness and operational transparency (Heilig & Voß, 2017).

Through these virtual models, port managers are able to monitor vessel arrivals, container movements, terminal congestion levels, and cargo handling processes in real time. The integration of digital twin systems with sensor technologies and port management platforms allows operational data to be continuously updated, ensuring that port managers have access to accurate and timely information. This capability significantly improves operational visibility and allows port authorities to identify potential operational disruptions before they affect port activities (Batty, 2018).

Real-time monitoring also enables faster and more informed decision-making in port logistics management. By analyzing real-time operational data through digital twin platforms, port managers can optimize vessel scheduling, coordinate terminal activities, and allocate port resources more efficiently. These improvements contribute to smoother cargo flows and reduce operational delays within port logistics systems (Ivanov, Dolgui, & Sokolov, 2019).

Furthermore, digital twin technology supports predictive monitoring and scenario simulation within port environments. By using historical and real-time data, digital twin systems can simulate different operational scenarios and help port authorities anticipate potential disruptions such as vessel congestion, terminal bottlenecks, or logistics delays. This predictive capability strengthens operational planning and enhances the resilience of maritime logistics systems (Tao et al., 2019).

In the Indonesian context, the adoption of digital technologies in port logistics management is increasingly recognized as a strategic priority for improving national logistics performance. Research on smart port development in Indonesia indicates that advanced digital technologies, including digital twins, Internet of Things (IoT), and integrated logistics platforms, can enhance operational visibility and support more efficient port management practices (Prasetyo & Nugroho, 2022).

Overall, the implementation of digital twin technology represents an important step toward the development of smart port systems. By enabling real-time monitoring, improving operational visibility, and supporting data-driven decision-making, digital twin platforms can significantly enhance the efficiency and effectiveness of modern port logistics operations (Heilig & Voß, 2017).

Operational Simulation and Predictive Decision-Making

Another important finding of this study is the role of digital twin technology in supporting simulation-based decision-making within port logistics systems. Digital twin models enable port operators to simulate different operational scenarios by combining real-time data, historical operational records, and advanced simulation algorithms. Through these virtual simulations, port authorities can evaluate how changes in operational conditions may affect logistics performance and port capacity utilization (Tao, Zhang, Liu, & Nee, 2019).

Digital twin platforms provide a virtual environment where different logistics scenarios can be tested without disrupting actual port operations. This capability is particularly valuable in complex port environments where operational decisions must consider multiple factors, such as vessel scheduling, cargo handling capacity, berth availability, and logistics infrastructure constraints. By simulating various operational strategies, port managers can identify the most efficient approaches to managing port activities (Heilig & Voß, 2017).

For example, digital twin systems can simulate the impact of increased container volumes on terminal congestion and evaluate how changes in berth allocation or container handling schedules may influence port performance. These simulations allow port operators to assess potential bottlenecks within terminal operations and develop appropriate operational strategies before congestion occurs. As a result, digital twin technology helps improve operational planning and reduces the risk of disruptions within port logistics systems (Batty, 2018).

In addition, simulation-based decision-making supported by digital twins allows port authorities to optimize the allocation of logistics resources. Port managers can test alternative scheduling strategies, cargo handling procedures, and vessel traffic management policies in a virtual environment before implementing them in real operations. This approach enhances the quality of decision-making and supports more efficient resource utilization across port logistics activities (Ivanov, Dolgui, & Sokolov, 2019).

The predictive capabilities of digital twin systems also enable port authorities to anticipate operational challenges and implement proactive solutions to maintain smooth logistics operations. By analyzing simulation results, port managers can develop contingency plans to address potential disruptions such as unexpected cargo surges, vessel arrival delays, or terminal capacity limitations. These proactive planning capabilities strengthen the resilience of port logistics systems and contribute to more reliable maritime supply chain operations (Tao et al., 2019).

In the Indonesian context, the development of smart port initiatives has encouraged the adoption of advanced digital technologies that support data-driven decision-making in port management. Studies on digital transformation in Indonesian port systems highlight that simulation-based technologies such as digital twins can improve operational planning, enhance logistics coordination, and support more efficient port infrastructure management (Prasetyo & Nugroho, 2022).

Overall, digital twin technology plays an important role in enabling simulation-based decision-making in modern port logistics systems. By allowing port managers to test operational strategies in virtual environments, anticipate potential disruptions, and optimize resource allocation, digital twin platforms contribute significantly to improving the efficiency and reliability of maritime logistics operations (Heilig & Voß, 2017).

Improving Resource Allocation and Infrastructure Management

The study also found that digital twin technology helps optimize resource allocation within port operations. Resource allocation is a critical aspect of port management because ports operate complex logistics systems that involve multiple infrastructures, equipment, and operational processes. Inefficient allocation of resources such as cranes, transport vehicles, and terminal facilities can lead to operational delays, congestion, and increased logistics costs. Therefore, effective management of operational resources is essential for maintaining efficient port performance and ensuring the smooth flow of cargo movement (Rodrigue & Notteboom, 2017).

By analyzing real-time operational data, digital twin systems can identify inefficiencies in the use of port infrastructure and logistics equipment. Digital twin platforms integrate data from various operational

systems, including terminal operating systems, cargo handling equipment, and vessel traffic monitoring systems. Through real-time monitoring and data analytics, these platforms allow port managers to observe operational patterns, detect bottlenecks, and evaluate the performance of logistics equipment. According to Tao and Zhang (2017), digital twin technologies enable organizations to continuously monitor physical systems through virtual models that support real-time performance analysis and operational optimization.

This information allows port managers to optimize the allocation of cranes, transport vehicles, and terminal facilities. For example, digital twin simulations can help determine the most efficient scheduling of quay cranes, container handling equipment, and yard transport systems. By analyzing operational data, digital twin systems can also support predictive decision-making, enabling port authorities to anticipate potential congestion and allocate resources more effectively. Scholars emphasize that data-driven logistics management can significantly improve operational efficiency and reduce resource wastage in complex transportation infrastructures (Heilig, Schwarze, & Voß, 2017; Batty, 2018).

Improved resource allocation contributes to higher operational productivity and reduces idle time for port equipment. When logistics equipment is allocated more efficiently, port operations can handle higher cargo volumes while minimizing operational delays. Reduced idle time also increases the utilization rate of port infrastructure, allowing ports to maximize the value of their operational assets. Efficient equipment utilization is particularly important in modern port logistics systems where operational capacity must continuously adapt to fluctuations in global trade activities.

In the Indonesian context, improving the efficiency of port infrastructure utilization has become a strategic priority for strengthening national logistics performance. As an archipelagic country with extensive maritime trade routes, Indonesia relies heavily on efficient port operations to support domestic distribution networks and international trade flows. Researchers highlight that optimizing the utilization of port resources is essential for improving logistics performance and reducing supply chain inefficiencies within Indonesia's maritime sector (Suyono, 2018; Santoso & Riyanto, 2020).

Furthermore, digital transformation initiatives in Indonesia's logistics sector increasingly emphasize the adoption of advanced information technologies to improve operational efficiency and infrastructure management. Indrajit (2016) explains that the integration of digital information systems in infrastructure management can significantly improve the efficiency of resource utilization and enhance the quality of operational decision-making. Similarly, Nugroho (2021) notes that digital governance and data-driven decision-making frameworks can support more efficient management of public infrastructure systems by enabling institutions to analyze operational data and optimize resource allocation.

Nasrullah (2017) also highlights that digital communication and information platforms facilitate the integration of operational data across different institutions and operational units. In the context of port logistics operations, this integration enables port authorities, terminal operators, and logistics providers to coordinate resource allocation more effectively through shared digital platforms.

As a result, digital twin systems support more efficient management of port infrastructure and improve the overall performance of logistics operations within the port environment. By providing real-time insights, predictive analytics, and integrated data platforms, digital twin technologies allow port managers to optimize operational resources, reduce inefficiencies, and improve logistics productivity. Ultimately, these improvements contribute to the development of more intelligent, adaptive, and efficient smart port systems capable of supporting increasingly complex global supply chains.

Enhancing Collaboration Among Port Stakeholders

Another significant finding relates to the role of digital twin platforms in improving collaboration among stakeholders involved in port logistics operations. Port logistics systems involve multiple actors, including port authorities, terminal operators, shipping companies, logistics providers, and customs agencies. These actors operate within an interconnected logistics ecosystem where coordination and information sharing are essential for ensuring efficient cargo movement and minimizing operational disruptions. In complex logistics environments such as seaports, ineffective coordination among stakeholders may lead to delays, congestion, and inefficiencies in the supply chain (Heilig, Schwarze, & Voß, 2017).

Effective coordination among these stakeholders is therefore essential for maintaining efficient supply chain operations. Ports function as critical nodes within global trade networks, where the movement of goods depends on synchronized activities among various organizations and institutions. Scholars emphasize that collaborative governance and information integration are key elements for improving the performance of port

logistics systems (Notteboom & Rodrigue, 2005; Rodrigue & Notteboom, 2017). Without proper coordination mechanisms, fragmented decision-making among stakeholders may reduce operational efficiency and increase logistics costs.

Digital twin platforms provide a shared information environment that allows stakeholders to access operational data and monitor port activities in real time. Digital twin technology creates a virtual representation of physical infrastructure and operational processes, enabling stakeholders to simulate, analyze, and optimize logistics activities. Through integrated data systems, stakeholders can obtain real-time information regarding vessel movements, cargo handling processes, terminal capacity, and transportation flows. According to Tao and Zhang (2017), digital twin technology allows organizations to monitor physical systems through digital simulations, which can significantly improve operational decision-making and system coordination.

This shared visibility helps improve communication among stakeholders and supports more coordinated logistics planning. When stakeholders have access to the same operational data, they can make more informed decisions regarding scheduling, resource allocation, and logistics management. Improved data transparency also reduces information asymmetry among stakeholders and enhances trust within collaborative logistics networks. As a result, digital twin technology contributes to stronger collaboration across the maritime logistics ecosystem and supports more efficient supply chain coordination (Batty, 2018).

In the Indonesian context, collaboration among port stakeholders has become increasingly important as the country continues to develop its maritime infrastructure and strengthen its logistics systems. As an archipelagic country with extensive maritime trade activities, Indonesia relies heavily on efficient port operations to support national economic growth and international trade. Researchers highlight that improving coordination among port authorities, logistics providers, and government agencies is essential for enhancing the performance of Indonesia's port logistics systems (Suyono, 2018; Santoso & Riyanto, 2020).

Furthermore, digital transformation initiatives in Indonesia's maritime sector have increasingly emphasized the use of information technology to improve logistics integration and operational transparency. Indrajit (2016) explains that digital platforms and integrated information systems can significantly enhance coordination among stakeholders by providing centralized data access and improving communication across institutions. Similarly, Nugroho (2021) argues that digital governance frameworks can facilitate collaborative decision-making among public and private sector actors involved in complex infrastructure systems.

Nasrullah (2017) also emphasizes that digital communication technologies play a critical role in facilitating institutional collaboration by enabling faster information exchange and improving the accessibility of shared data platforms. In the context of port logistics operations, digital twin platforms can therefore serve as collaborative tools that support data-driven coordination among stakeholders and improve the overall efficiency of maritime logistics networks.

Overall, the findings suggest that digital twin technology has strong potential to enhance stakeholder collaboration in port logistics systems. By providing integrated data platforms, real-time operational monitoring, and shared information environments, digital twin systems can strengthen coordination among port authorities, logistics operators, and government agencies. Improved collaboration among these stakeholders can ultimately contribute to more efficient logistics operations, reduced operational disruptions, and enhanced competitiveness of maritime supply chains.

Challenges in Digital Twin Implementation

Despite the advantages of digital twin technology, the study also identified several challenges associated with its implementation in port logistics environments. One major challenge involves the complexity of integrating multiple data sources into a unified digital twin system. Ports operate a wide range of operational technologies and information systems, including terminal operating systems, vessel traffic management systems, cargo tracking platforms, and logistics management software. Integrating these heterogeneous systems into a unified digital twin environment requires high levels of data interoperability and system compatibility. Scholars emphasize that the integration of diverse digital infrastructures is one of the most complex aspects of implementing digital twin technologies in large-scale industrial environments (Tao & Zhang, 2017; Batty, 2018).

Ports are dynamic operational environments where multiple activities occur simultaneously, including cargo handling, vessel scheduling, and land transportation coordination. To accurately replicate these activities within a digital twin platform, large volumes of real-time data must be continuously collected and processed. This requirement often creates challenges related to data standardization, system integration, and technological

compatibility among existing operational platforms (Heilig, Schwarze, & Voß, 2017). Without proper integration frameworks, digital twin systems may struggle to provide reliable simulations and accurate operational insights.

Another challenge relates to the high investment costs required for developing digital twin infrastructure. Implementing digital twin systems requires advanced data platforms, sensor networks, Internet of Things (IoT) devices, and data analytics capabilities. These technological components must be installed across port infrastructure in order to collect real-time operational data. In addition, ports must invest in computing systems and digital platforms capable of processing large volumes of data and generating digital simulations of operational processes. According to Tao et al. (2019), the development of digital twin environments requires substantial financial investment in digital infrastructure, system integration, and technological maintenance.

These technological investments may represent a significant financial burden for some ports, particularly those operating in developing economies or with limited technological resources. Smaller ports may face difficulties in allocating sufficient budgets for digital transformation initiatives, which can slow down the adoption of advanced technologies such as digital twin platforms. Consequently, financial capacity becomes an important factor influencing the pace of digital transformation in maritime logistics systems.

In the Indonesian context, investment constraints and technological readiness are important issues affecting the adoption of digital technologies in port logistics systems. As an archipelagic country with extensive maritime trade activities, Indonesia has prioritized the modernization of its port infrastructure to improve logistics efficiency and support national economic development. However, researchers note that implementing advanced digital systems in Indonesian ports requires substantial investment in technological infrastructure as well as institutional coordination among relevant stakeholders (Suyono, 2018; Santoso & Riyanto, 2020).

Indonesian scholars also emphasize that digital transformation in infrastructure sectors must be supported by strategic planning and sustainable investment frameworks. Indrajit (2016) explains that successful implementation of digital technologies in public infrastructure requires strong institutional commitment, adequate funding, and long-term digital development strategies. Without these elements, digital innovation initiatives may encounter significant operational and financial barriers.

In addition to technological and financial challenges, organizational adaptation is required to fully utilize digital twin technologies. The implementation of digital twin systems often requires significant changes in organizational practices, operational workflows, and decision-making processes. Port authorities and logistics organizations must develop new technical capabilities and train personnel to manage digital systems effectively. This includes developing expertise in data analytics, system management, and digital infrastructure maintenance.

Human resource capacity is therefore an important factor in the successful implementation of digital twin technologies. According to Nugroho (2021), digital transformation in the public and infrastructure sectors requires significant investment in human capital development to ensure that organizations can effectively manage and utilize advanced technologies. Similarly, Nasrullah (2017) highlights that technological innovation in digital communication and information systems must be accompanied by improved digital literacy and institutional capacity.

Without adequate human resource development, the potential benefits of digital twin technology may not be fully realized. Even when digital infrastructure is successfully implemented, organizations may struggle to utilize these systems effectively if personnel lack the necessary technical skills and operational knowledge. Therefore, continuous training programs, professional development initiatives, and collaboration with technological experts are essential for ensuring the successful adoption of digital twin technologies in port logistics systems.

Overall, these findings suggest that while digital twin technology offers significant opportunities for improving operational efficiency and collaboration in port logistics systems, its implementation also presents several technological, financial, and organizational challenges. Addressing these challenges requires integrated strategies that combine technological investment, institutional coordination, and human resource development. By adopting comprehensive digital transformation strategies, port authorities and logistics stakeholders can maximize the benefits of digital twin technologies while minimizing the challenges associated with their implementation.

Implications for Smart Port Development

The findings of this study demonstrate that digital twin technology represents an important innovation in the development of smart ports. The concept of smart ports refers to the integration of advanced digital technologies, data analytics, and intelligent infrastructure to improve the efficiency, sustainability, and resilience of port operations. In this context, digital twin systems play a crucial role by creating virtual representations of physical port infrastructure and operational processes. These digital models allow port authorities and logistics operators to monitor activities, simulate operational scenarios, and optimize decision-making processes in real time (Tao & Zhang, 2017; Batty, 2018).

By enabling real-time monitoring, predictive simulation, and data-driven decision-making, digital twin systems can significantly improve the efficiency and resilience of port logistics operations. Through the integration of sensor networks, Internet of Things (IoT) devices, and advanced data analytics, digital twin platforms provide continuous operational insights that help port managers identify potential disruptions and optimize resource allocation. Scholars highlight that real-time digital monitoring systems can significantly reduce operational uncertainties and enhance the responsiveness of port logistics systems (Heilig, Schwarze, & Voß, 2017; Rodrigue & Notteboom, 2017).

In addition, predictive simulation capabilities allow digital twin systems to model different operational scenarios and forecast potential logistics disruptions before they occur. By analyzing historical data and real-time operational information, digital twin technologies enable port authorities to anticipate congestion, optimize vessel scheduling, and improve cargo handling efficiency. These predictive capabilities are particularly important in modern maritime logistics environments where supply chains are increasingly complex and dynamic.

For port authorities and logistics managers, investing in digital twin technologies can support more intelligent port management and enhance the competitiveness of maritime logistics systems. Ports are critical nodes in global supply chains, and their operational performance directly influences the efficiency of international trade. As global trade volumes continue to increase, ports must adopt advanced digital technologies to improve operational efficiency and maintain competitiveness within the global maritime industry (Notteboom & Rodrigue, 2005).

In the Indonesian context, the development of smart port systems has become increasingly important as the country seeks to strengthen its maritime infrastructure and logistics capabilities. As an archipelagic country with extensive maritime trade networks, Indonesia relies heavily on efficient port operations to support national economic growth. Researchers emphasize that digital transformation in the maritime sector can significantly improve logistics efficiency and strengthen Indonesia's competitiveness in international trade (Suyono, 2018; Santoso & Riyanto, 2020).

Indonesian scholars also highlight the importance of digital innovation in modernizing port management systems. According to Indrajit (2016), the adoption of digital technologies in public infrastructure sectors can improve operational transparency, enhance coordination among stakeholders, and increase the efficiency of service delivery. Similarly, Nugroho (2021) notes that digital transformation initiatives in Indonesia must focus on developing integrated digital platforms that support data-driven decision-making and collaborative governance.

However, the successful implementation of digital twin technology requires strong digital infrastructure, stakeholder collaboration, and continuous development of technical expertise. Digital twin platforms rely heavily on reliable data networks, integrated information systems, and advanced analytical tools. Without adequate digital infrastructure, the effectiveness of digital twin systems may be limited. Furthermore, collaboration among port authorities, logistics operators, and government institutions is essential for ensuring that digital systems operate within integrated logistics ecosystems.

Human resource development also plays an important role in the successful adoption of digital twin technologies. Port authorities and logistics organizations must develop technical expertise in areas such as data analytics, digital system management, and information technology infrastructure. Nasrullah (2017) emphasizes that technological innovation in digital communication and information systems must be accompanied by improvements in digital literacy and institutional capacity to ensure effective implementation.

Overall, digital twin technology has the potential to transform traditional port logistics operations into more intelligent and adaptive smart port systems capable of responding to the increasing complexity of global supply chains. By integrating real-time data monitoring, predictive simulation, and collaborative digital platforms, digital twin systems can support more efficient port management, improve logistics coordination,

and enhance the resilience of maritime infrastructure. Consequently, the adoption of digital twin technologies represents an important step toward the development of advanced smart port ecosystems that can support sustainable and competitive maritime logistics systems in the future.

CONCLUSIONS

This study explored the role of digital twin technology in supporting smart port operations through the context of port digitalization at the Port of Busan. The findings indicate that digital twin technology plays a significant role in improving operational efficiency, enhancing decision-making processes, and strengthening coordination among stakeholders involved in port logistics operations. By integrating real-time operational data with virtual models of port infrastructure and logistics activities, digital twin systems enable port authorities to monitor and manage port operations more effectively.

The study highlights that digital twin technology provides several operational advantages for port management. Real-time monitoring capabilities allow port managers to track vessel movements, container handling activities, and terminal operations more accurately. In addition, simulation-based analysis enables port authorities to evaluate potential operational scenarios and develop proactive strategies to address congestion, resource constraints, and logistics disruptions. These capabilities contribute to more efficient and resilient port logistics systems.

Another important finding of this study is the role of digital twin technology in improving resource allocation and infrastructure management. By analyzing operational data and identifying inefficiencies in port operations, digital twin systems help optimize the use of port equipment, terminal facilities, and logistics resources. This optimization improves productivity and reduces operational delays within port logistics environments.

Furthermore, digital twin platforms enhance collaboration among stakeholders within the maritime logistics ecosystem. Shared access to operational data allows port authorities, shipping companies, terminal operators, and logistics providers to coordinate their activities more effectively. Improved information sharing contributes to better supply chain coordination and supports more integrated port logistics operations.

Despite these benefits, the implementation of digital twin technology also presents several challenges. The integration of multiple data sources into unified digital systems requires advanced technological infrastructure and strong data management capabilities. High investment costs and the need for skilled personnel represent additional barriers to digital twin adoption. Therefore, successful implementation of digital twin systems requires not only technological innovation but also organizational readiness and workforce capability development.

Overall, the findings of this study demonstrate that digital twin technology represents an important driver of digital transformation in port logistics systems. By enabling data-driven port management and predictive operational planning, digital twin systems support the development of smarter and more adaptive port operations. These insights provide valuable implications for port authorities, logistics operators, and policymakers seeking to enhance port performance and strengthen the competitiveness of maritime supply chains in an increasingly digital global logistics environmen.

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