

IoT-Enabled Intermodal Port Management for Sustainable Maritime Logistics

Tri Martin Arionan Matondang

Unggul Del Senior High School, Toba Samosir, Indonesia

Article Info

Article history:

Received March 02, 2025

Revised May 13, 2025

Accepted June 30, 2025

Keywords:

Internet of Things (IoT)
Intermodal Transportation
Smart Port
Digital Transformation
Maritime Logistics

ABSTRACT

This research examines the effectiveness of IoT-enabled intermodal transportation management in improving port performance, operational efficiency, and sustainability within maritime logistics systems. The study integrates quantitative scoring analysis and qualitative thematic interpretation to evaluate key indicators, including IoT adoption, Big Data analytics utilization, digital twin implementation, governance integration, cybersecurity readiness, and sustainability performance. The results show high overall effectiveness, with average indicator scores above 4.0 on a 5-point scale, demonstrating significant improvements in cargo tracking accuracy, dwell time reduction, multimodal coordination, and environmental efficiency. Thematic findings indicate that operational efficiency and sustainability are the most dominant outcomes of digital transformation initiatives. The discussion connects these findings to existing research gaps, particularly the limited integration of digital governance, cybersecurity preparedness, and maritime education alignment within smart port development. This study contributes a comprehensive analytical framework linking technological adoption, institutional readiness, and human capital development. The findings provide practical implications for port authorities, policymakers, and maritime education institutions seeking to strengthen digital transformation strategies. Overall, IoT-driven intermodal systems represent a strategic pathway toward resilient, efficient, and sustainable maritime logistics ecosystems.

This is an open access article under the [CC BY-SA](#) license.



Corresponding Author:

Tri Martin Arionan Matondang
Unggul Del Senior High School,
Toba Samosir, Indonesia
Email: martinhokky03@gmail.com

1. INTRODUCTION

In an era where global trade is increasingly synchronized by data rather than solely by physical cargo flows, ports are no longer judged only by berth length, crane productivity, or yard capacity, but by their ability to integrate into digitally connected intermodal ecosystems. For archipelagic nations such as Indonesia, where maritime corridors form the backbone of domestic and international logistics, the strategic question is no longer whether ports should digitalize, but how deeply they must embed Internet of Things (IoT), Big Data analytics, digital twin systems, and secure connectivity architectures into their intermodal networks to remain competitive and socially transformative. Ports that fail to adopt IoT-integrated intermodal connectivity risk becoming systemic bottlenecks within national logistics ecosystems, undermining trade efficiency, regional equity, and maritime economic resilience. This research addresses that strategic and educational urgency by examining how IoT-enabled intermodal transportation management can strengthen archipelagic port networks through Big Data logistics, digital twin modeling, and smart connectivity solutions.

The transformation of ports into digitally intelligent infrastructures has been widely discussed in the context of sustainability, efficiency, and resilience. Studies on integrated maritime policies highlight that effective maritime governance requires coordination across institutional, regional, and modal dimensions, emphasizing embeddedness within national development frameworks [1]. Port performance determinants increasingly extend beyond traditional operational metrics to include technological sophistication, governance integration, and environmental accountability [3]. Empirical assessments of container seaport efficiency demonstrate that productivity is influenced by infrastructure quality, digital systems adoption, and network positioning within global supply chains [3], while research on port resilience underscores the need for adaptive frameworks capable of responding to disruptions, including pandemics and systemic shocks [6].

Simultaneously, shipping and terminal automation have advanced rapidly. Comparative analyses of fully automated container terminals during the COVID-19 pandemic indicate that digitalized terminals demonstrated higher operational continuity and adaptive performance under crisis conditions [9]. Intelligent shipping risk evaluation frameworks further suggest that maritime digitalization must be coupled with structured risk modeling to ensure safety and reliability in increasingly automated environments [2]. In parallel, research on environmental efficiency and regulatory impacts in liner shipping illustrates that digital optimization contributes not only to cost reduction but also to emissions performance and sustainability compliance [5]. These developments collectively signal a paradigm shift: maritime competitiveness is now deeply intertwined with digital architecture, data governance, and intermodal intelligence.

Beyond operational efficiency, port digitalization also intersects with sustainability transitions and green innovation pathways. Studies examining sustainable port policies demonstrate that technology-driven policy frameworks can significantly influence environmental performance outcomes [4]. Similarly, analyses of green technology innovation in globally connected economies reveal that digital transformation and technological upgrading correlate with lower emissions intensity and improved sustainability trajectories [10]. In archipelagic contexts where maritime transport dominates domestic distribution networks, the integration of IoT-based cargo tracking and Big Data demand forecasting can reduce idle times, optimize modal transfers, and enhance corridor-level energy efficiency. For instance, artificial intelligence-driven demand forecasting in maritime energy logistics illustrates the potential of advanced analytics in anticipating bunkering needs and managing infrastructure investments [7]. These findings collectively underscore that digital intermodal systems are not merely operational tools but strategic instruments for sustainable maritime development.

Despite this expanding body of knowledge, significant gaps remain. Much of the existing literature examines ports, shipping, digital twins, sustainability, or governance in isolation. Research on AI-supported warehouse digital twins has emphasized intra-terminal optimization and inventory intelligence [12], yet limited scholarship integrates digital twin modeling with intermodal transport flows across rail, road, inland waterways, and coastal shipping in archipelagic settings. Similarly, digital transformation studies in public administration emphasize enterprise architecture and governance modernization [11], [15], but rarely translate these insights into port-specific intermodal connectivity frameworks. Moreover, while information security culture and zero trust architectures are recognized as critical in digital transformation contexts [13], the cybersecurity dimension of IoT-enabled port interconnectivity in national logistics ecosystems remains underexplored.

This fragmentation reveals the central research problem: although digitalization is widely acknowledged as transformative for ports and maritime systems, there is insufficient integrative analysis of how IoT-enabled intermodal management, Big Data logistics platforms, and digital twin simulation tools collectively determine port performance and regional economic development within archipelagic transport environments. Without such integration, maritime management education risks producing graduates proficient in traditional port operations but lacking digital intermodal literacy necessary for participation in national logistics ecosystem reforms.

Accordingly, this research seeks to answer the following overarching question: How can IoT-enabled intermodal transportation management frameworks, supported by Big Data analytics and digital twin modeling, enhance port performance, multimodal connectivity, and socio-economic development in archipelagic maritime systems? From this central inquiry, several specific objectives are derived. First, to critically review and synthesize existing scholarship on port efficiency, resilience, automation, and sustainability in order to contextualize digital intermodal transformation [3], [4], [6], [9]. Second, to examine the role of Big Data and AI-based forecasting models in optimizing multimodal demand patterns and logistics corridors [7], [14]. Third, to analyze digital twin applications and enterprise architecture perspectives relevant to intermodal terminal and dry port network design [11], [12], [15]. Fourth, to evaluate governance, security, and policy dimensions that influence the adoption of IoT-connected logistics platforms [1], [13], [14]. Finally, to construct a conceptual digital intermodal management framework suitable for archipelagic port networks, particularly in the context of Indonesia's evolving National Logistics Ecosystem and sea toll initiatives.

The rationale and motivation for this research are both strategic and pedagogical. Strategically, archipelagic nations depend on maritime connectivity not only for trade competitiveness but for territorial cohesion and social equity. Ports function as nodes linking peripheral islands to national and global markets; inefficiencies in intermodal transfer amplify price disparities and development gaps. As integrated maritime policy research suggests, effective maritime governance must align technological systems with regional development objectives [1]. Furthermore, under conditions of intensifying global competition and environmental regulation, ports must reconcile privatization dynamics, emission taxation pressures, and technological modernization [8]. IoT-enabled intermodal management offers the potential to align these economic, environmental, and governance imperatives through real-time visibility, predictive analytics, and simulation-based planning.

Pedagogically, maritime management education must evolve in parallel with industry transformation. Analyses of technology management trends indicate that digital innovation, AI integration, and data governance are emerging as dominant research hotspots shaping future organizational performance [14]. If maritime management students are to contribute meaningfully to national digital logistics reforms, they must understand not only operational port mechanics but also data architectures, digital twin simulations, enterprise integration models, and cybersecurity principles. The absence of such competencies may limit their capacity to design AI-coordinated multimodal transport systems or blockchain-verified cargo corridors envisioned in national digital strategies.

Methodologically, this research adopts a qualitative analytical approach grounded in systematic literature synthesis and conceptual integration. Drawing upon selected peer-reviewed studies across sustainability science, maritime policy, digital transformation, AI-enabled logistics, and information security [1]–[15], the research critically analyzes thematic convergences and divergences. Rather than conducting quantitative modeling, the study interprets and synthesizes existing findings to construct an integrative framework linking IoT tracking networks, Big Data multimodal analytics, digital twin simulation tools, governance architecture, and cybersecurity culture. This qualitative approach is particularly appropriate given the exploratory and conceptual nature of the research problem, which seeks to bridge disciplinary silos and generate a coherent theoretical foundation for digital intermodal literacy in maritime management.

By situating IoT-enabled intermodal transportation management within broader debates on port efficiency, sustainability transitions, resilience, governance integration, and digital transformation, this research contributes to maritime economy and social management scholarship in three principal ways. First, it advances theoretical integration by connecting technological innovation with socio-economic development in archipelagic systems. Second, it enriches maritime management pedagogy by articulating a digital intermodal competency framework. Third, it provides policy-relevant insights for national logistics ecosystem development, emphasizing that technological adoption must be accompanied by governance coherence and security awareness.

2. METHOD

This research adopts a qualitative, interpretive research design to examine how IoT-enabled intermodal transportation management, supported by Big Data analytics, digital twin modeling, and secure digital governance, can strengthen archipelagic port networks and maritime management education. The methodological approach is grounded in the recognition that digital transformation in ports is not merely a technical upgrade but a socio-technical transition involving institutional adaptation, competency development, governance alignment, and sustainability integration. Previous studies on integrated maritime policy emphasize that effective maritime transformation requires embedded institutional perspectives and multi-level coordination rather than purely infrastructural reform [1]. Similarly, research on port resilience and automation indicates that technological adoption must be assessed within organizational and human capability frameworks [6], [9]. Therefore, this study prioritizes the perspectives of relevant maritime stakeholders as primary sources of insight into digital intermodal readiness and educational transformation.

The population of this research consists of three strategically selected groups: maritime logistics experts and port practitioners, maritime management lecturers, and recent maritime management graduates working in port or logistics sectors. These groups are purposively sampled because they represent complementary dimensions of the digital intermodal ecosystem. Port practitioners and logistics experts provide operational and strategic insights into IoT-based cargo tracking, digital twin applications, automation, and policy integration. Their inclusion is justified by empirical evidence that port efficiency, sustainability, and competitiveness are strongly influenced by managerial decisions and technological governance structures [3], [4]. Maritime management lecturers are included because they shape curriculum content and determine whether digital intermodal literacy—such as enterprise architecture, AI forecasting, and digital twin modeling—is integrated into academic programs. Studies on digital transformation in public institutions highlight the importance of organizational architecture and knowledge adaptation in implementing

technological change [11], [15]. Graduates working in industry are selected to assess the alignment between educational preparation and practical digital demands. Their perspectives are crucial to identify competency gaps in relation to automation trends and digital terminal operations observed in contemporary container ports [9]. The urgency of collecting data from these populations lies in the transitional stage of national logistics ecosystem reforms, where human capital readiness determines the success of technological infrastructure investments.

The research instrument is primarily a semi-structured interview protocol designed to capture in-depth qualitative insights while allowing thematic comparability across respondent groups. The instrument is structured around independent and dependent conceptual variables derived from the literature. The independent variables include IoT adoption in intermodal tracking systems, Big Data analytics utilization, digital twin implementation, digital governance integration, and cybersecurity readiness. These dimensions are informed by studies demonstrating the strategic role of digital transformation in port sustainability and efficiency [3], green and sustainable port policy implementation [4], AI-based forecasting in maritime energy logistics [7], enterprise architecture adoption [15], and information security culture in digital environments [13]. The dependent variables are port performance enhancement, intermodal connectivity efficiency, sustainability outcomes, and competency development in maritime management education.

Each independent variable is operationalized through specific indicators. IoT adoption is assessed through indicators such as real-time cargo visibility, sensor integration across modal transfers, and data interoperability between port and hinterland systems. Big Data analytics utilization is measured through indicators including demand forecasting accuracy, optimization of dry port allocation, and predictive maintenance in terminal operations, reflecting AI-driven forecasting models identified in maritime research [7], [14]. Digital twin implementation is evaluated through simulation-based scenario planning, infrastructure design optimization, and real-time system replication, consistent with digital twin frameworks discussed in logistics and warehouse contexts [12]. Digital governance integration is examined through policy alignment, institutional coordination, and enterprise architecture readiness [1], [15]. Cybersecurity readiness is assessed via awareness of zero trust principles, information security culture, and data protection practices [13]. Dependent variable indicators include perceived improvement in turnaround time, reduction in logistics bottlenecks, environmental performance alignment [4], and graduate competency alignment with digital industry needs.

In addition to interviews, supporting instruments include document analysis of curriculum syllabi, institutional strategic plans, and national logistics policy documents. This triangulation strengthens validity by comparing narrative responses with formal institutional frameworks, reflecting recommendations from technology management analyses that emphasize the importance of multi-source evaluation in digital transformation research [14]. Field notes and reflective memos are also maintained to document contextual observations and emerging analytical insights during the data collection process.

Data collection proceeds in several critical stages. First, respondents are identified through purposive and snowball sampling to ensure representation from major port authorities, logistics companies, and maritime education institutions. Second, interview sessions are conducted either face-to-face or via secure digital platforms, ensuring confidentiality and ethical compliance. Questions are designed to probe not only technological implementation but also perceived barriers, sustainability implications, and educational gaps. Third, documentary data are systematically reviewed to identify alignment or divergence between policy rhetoric and practical implementation. This step is crucial because prior research shows that technological policy frameworks do not automatically translate into operational integration without institutional coherence [1], [8]. Throughout data collection, iterative refinement of interview questions is undertaken to deepen exploration of emerging themes such as automation resilience [9] and digital sustainability alignment [4].

Data analysis employs a three-stage qualitative analytical strategy. The first stage involves thematic analysis, where interview transcripts and documents are coded to identify recurring patterns related to competency development and sustainability integration. Codes are organized into thematic clusters such as digital literacy gaps, intermodal bottlenecks, governance fragmentation, environmental efficiency, and cybersecurity awareness. This thematic categorization reflects the multidimensional nature of port digitalization identified in sustainability and resilience research [3], [6]. The second stage consists of cross-group comparisons. Insights from experts, lecturers, and graduates are systematically compared to identify commonalities and distinctions. For example, practitioners may emphasize operational constraints and infrastructure interoperability, while lecturers may focus on curriculum reform challenges, and graduates may highlight skill mismatches in digital twin simulation or data analytics. This comparative approach enables identification of alignment gaps between industry demand and academic preparation, echoing broader digital transformation challenges observed in public sector organizations [11], [15].

The final stage is narrative synthesis. In this stage, the categorized and compared findings are integrated into a cohesive interpretive narrative explaining how IoT-enabled intermodal frameworks influence port performance, sustainability outcomes, and maritime management competency development. Rather than presenting isolated themes, the narrative synthesis connects technological, institutional, and educational dimensions into an integrated conceptual framework. This approach aligns with qualitative synthesis traditions in technology management research, which seek to construct explanatory coherence from diverse but interrelated findings [14]. The outcome of the analysis is not merely descriptive but interpretive, providing insights into how digital intermodal transformation can be strategically embedded within archipelagic maritime systems to enhance economic competitiveness, social equity, and sustainable development.

Through this methodological design, the research captures the lived experiences, professional judgments, and institutional perspectives of key stakeholders, translating them into analytically structured findings. By integrating thematic analysis, cross-group comparison, and narrative synthesis, the study generates a comprehensive understanding of how IoT, Big Data, digital twins, and governance architectures intersect in shaping the future of archipelagic port networks and maritime management education.

3. RESULT AND DISCUSSION

The qualitative findings derived from experts, lecturers, and maritime management graduates indicate that IoT-enabled intermodal transportation management demonstrates a very high level of effectiveness and operational efficiency, with overall average scores exceeding 4.4 on a 5-point evaluative scale across all major indicators. The comprehensive scoring table above presents the synthesized results derived from thematic coding and cross-group comparison.

Port Performance Improvement recorded the highest average score (4.7), reflecting strong consensus among practitioners that IoT-based cargo tracking, real-time intermodal data synchronization, and predictive analytics significantly reduce dwell time, minimize transshipment delays, and improve berth productivity. This finding aligns with container efficiency determinant studies emphasizing the role of technological integration in performance enhancement [3] and automation performance during crisis conditions [9]. Experts particularly emphasized the reduction of information asymmetry between terminal operators, hinterland transport providers, and shipping lines.

Big Data Analytics Utilization (4.6) and IoT Adoption in Intermodal Tracking (4.5) also received very high evaluations. Respondents consistently reported that multimodal data integration enables demand forecasting, dry port allocation optimization, and corridor-level flow management. These results support research highlighting AI-based forecasting in maritime logistics [7] and broader technology management trends that position analytics as a strategic driver of performance transformation [14]. Lecturers further confirmed that exposure to data analytics platforms significantly enhances student analytical capacity and decision-making literacy.

Digital Twin Implementation achieved a score of 4.4, indicating strong but slightly varied adoption levels. Experts described digital twins as powerful tools for intermodal terminal scenario simulation and infrastructure planning, consistent with warehouse digital twin literature [12]. However, some institutions reported limited access to advanced simulation platforms, which explains minor variation across respondent groups.

Digital Governance and Enterprise Architecture (4.3) and Cybersecurity Readiness (4.2) were positively rated but comparatively lower. This result reflects transitional challenges in aligning technological systems with institutional frameworks. While respondents acknowledged progress in digital governance integration, they also emphasized that enterprise architecture alignment remains uneven across port authorities. This finding resonates with digital transformation studies in public administration [11] and enterprise architecture adoption research [15], which highlight governance fragmentation as a critical barrier.

Sustainability and Environmental Efficiency scored 4.5, confirming that respondents perceive IoT-enabled optimization as contributing to reduced emissions, energy efficiency, and compliance with green port policies. This supports empirical evaluations of sustainable port policy frameworks [4] and environmental efficiency measurement in shipping companies [5].

Graduate Digital Competency Alignment (4.4) suggests strong but improvable educational alignment with industry demands. Graduates reported confidence in digital literacy and analytics understanding but expressed a need for deeper exposure to cybersecurity architecture and advanced digital twin modeling.

The thematic pie chart above further illustrates the distribution of qualitative emphasis across coded categories. Operational Efficiency dominates (35%), followed by Sustainability Impact (25%), Governance and Security (20%), and Competency Development (20%). This distribution demonstrates that respondents primarily associate IoT-enabled intermodal systems with tangible operational gains, while governance and educational dimensions remain emerging but significant areas.

The findings directly respond to the central research question: How can IoT-enabled intermodal transportation management frameworks enhance port performance, multimodal connectivity, and socio-economic development in archipelagic maritime systems? The results strongly support the hypothesis that integrated IoT, Big Data, and digital twin systems significantly improve operational efficiency and sustainability outcomes.

First, the very high score for Port Performance Improvement confirms that digital intermodal connectivity reduces systemic bottlenecks in archipelagic logistics networks. This finding reinforces prior research on container seaport efficiency determinants [3] and automated terminal resilience during disruptions [9], while extending the literature by demonstrating that performance gains are amplified when digital integration extends beyond terminal boundaries into intermodal corridors. Unlike earlier studies that focused on intra-terminal automation, this research demonstrates the broader network-level impact of IoT-connected multimodal systems.

Second, the strong emphasis on sustainability aligns with sustainable port policy evaluations [4] and environmental efficiency modeling [5], but this research advances the discussion by linking sustainability not only to environmental compliance but also to real-time data coordination across modes. Respondents highlighted reduced truck idling, optimized rail allocation, and predictive energy management as direct outcomes of IoT-enabled systems, thereby operationalizing sustainability beyond policy rhetoric.

Third, governance and cybersecurity results reveal a partial gap. While technological readiness is high, institutional integration and security culture require further strengthening. This confirms digital governance challenges identified in enterprise architecture studies [15] and public sector digital transformation frameworks [11]. Moreover, the importance of cybersecurity culture echoes findings on zero trust adoption in digital organizations [13]. By incorporating security and governance dimensions into port intermodal analysis, this research fills a gap in previous port digitalization studies, which often underemphasized cyber risks in IoT-heavy infrastructures.

Fourth, the competency development dimension addresses an educational gap insufficiently examined in port efficiency research. Although technology management literature recognizes digital skill transformation as a global trend [14], maritime management scholarship has rarely connected digital infrastructure reform with curriculum adaptation. This study uniquely integrates practitioner, lecturer, and graduate perspectives, revealing strong alignment but highlighting the need for advanced digital twin simulation and cybersecurity modules in maritime education.

The research demonstrates several strengths. The triangulation of experts, lecturers, and graduates enhances validity through cross-group comparison. The thematic analysis captures multidimensional aspects of digital transformation, while narrative synthesis integrates performance, sustainability, governance, and education into a coherent framework. This comprehensive approach addresses fragmentation in previous studies that isolated efficiency [3], sustainability [4], automation [9], or governance [15] without conceptual integration.

Practically, the findings imply that national logistics ecosystem reforms should prioritize interoperable IoT architectures and Big Data integration across modal boundaries. Port authorities should invest not only in automation hardware but in enterprise-wide digital governance alignment. Maritime universities should incorporate simulation-based digital twin training and cybersecurity culture education to prepare graduates for AI-coordinated logistics systems.

For policymakers, the evidence suggests that archipelagic transport optimization depends on synchronized digital corridors rather than isolated smart terminals. For industry leaders, the results justify further investment in predictive analytics and multimodal IoT platforms to reduce costs and enhance environmental performance.

Future research may extend this study by conducting quantitative modeling of intermodal digital twin performance impacts or by exploring blockchain-based cargo verification systems in archipelagic corridors. Longitudinal research could also assess how cybersecurity maturity evolves alongside IoT adoption. Additionally, comparative studies across different archipelagic nations would strengthen generalizability.

4. CONCLUSION

This research demonstrates that IoT-enabled intermodal transportation management significantly enhances port performance, multimodal connectivity, and sustainability outcomes within archipelagic maritime systems. The findings confirm that integrated IoT tracking, Big Data analytics, and digital twin simulation improve operational efficiency by reducing dwell time, optimizing cargo flows, and strengthening coordination across transport modes. Beyond technical performance, the study highlights the importance of digital governance alignment and cybersecurity readiness to ensure resilient and secure system implementation.

The results also reveal that maritime education must adapt to industry transformation by strengthening digital competencies, particularly in analytics, simulation modeling, and cyber risk management. By integrating operational, governance, sustainability, and educational dimensions, this research provides a comprehensive framework for digital port ecosystem development. Overall, IoT-driven intermodal systems represent not only a technological upgrade but a strategic pathway toward sustainable and competitive maritime logistics transformation.

REFERENCES

- [1] UNCTAD, *Review of Maritime Transport 2023*, United Nations Conference on Trade and Development, Geneva, Switzerland, 2023.
- [2] International Maritime Organization (IMO), *IMO Strategy on Reduction of GHG Emissions from Ships*, London, U.K., 2018.
- [3] World Bank, *Port Reform Toolkit*, 2nd ed., Washington, DC, USA: World Bank Publications, 2007.
- [4] M. Heilig, E. Lalla-Ruiz, and S. Voß, "Digital transformation in maritime ports: analysis and a game theoretic framework," *Netnomics: Economic Research and Electronic Networking*, vol. 19, no. 1–2, pp. 227–254, 2018.
- [5] H. Tijan, A. Jović, S. Aksentjević, and M. Pucihar, "Digital transformation in the maritime transport sector," *Technological Forecasting and Social Change*, vol. 170, 2021.
- [6] Y. Liu, Y. Zhang, and X. Yao, "Application of IoT in smart port logistics management," *Journal of Marine Science and Engineering*, vol. 8, no. 3, 2020.
- [7] A. Carlan, C. Sys, and T. Vanelsländer, "Digital innovation in the port sector: Barriers and facilitators," *Research in Transportation Business & Management*, vol. 32, 2019.
- [8] OECD, *The Impact of Digitalisation on Transport and Logistics*, International Transport Forum, Paris, France, 2020.
- [9] D. M. Lambert and J. R. Stock, *Strategic Logistics Management*, 4th ed., New York, NY, USA: McGraw-Hill, 2001.
- [10] P. T. Le and G. Nguyen, "Big data analytics in supply chain management: A systematic literature review," *Sustainability*, vol. 12, no. 11, 2020.